Energy Technology Perspectives 2016

Towards Sustainable Urban Energy Systems

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Energy Technology Perspectives 2016

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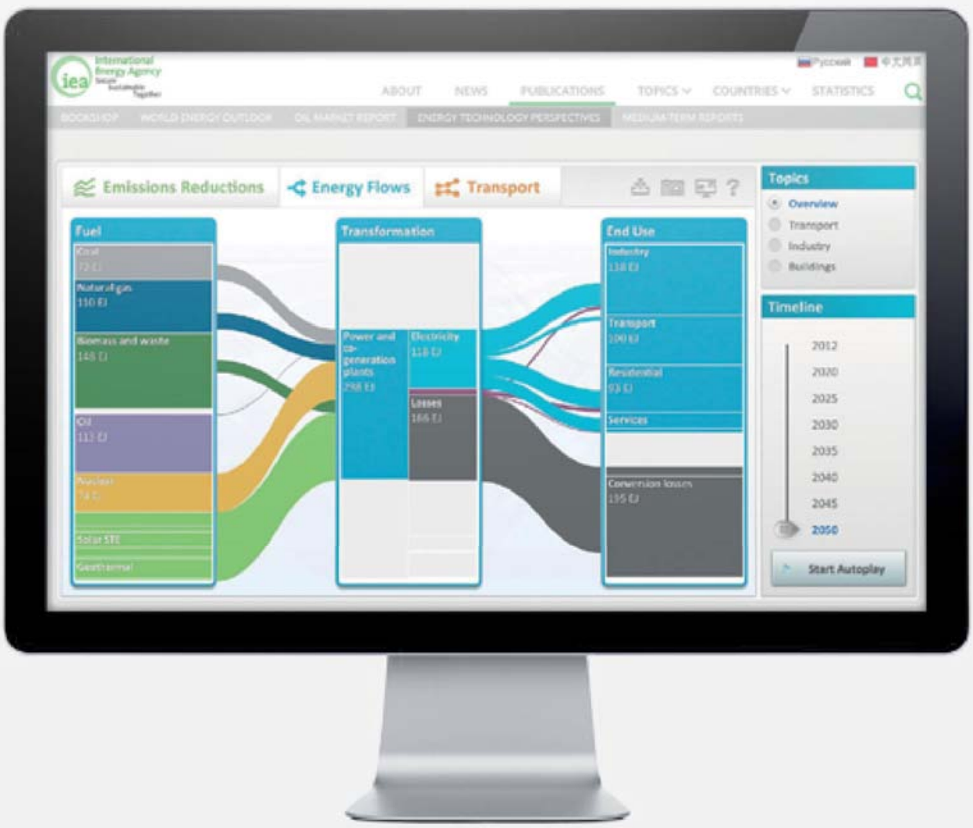

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The International Energy Agency (IEA), an autonomous agency, was established in November 1974. Its primary mandate was – and is – two-fold: to promote energy security amongst its member countries through collective response to physical disruptions in oil supply, and provide authoritative research and analysis on ways to ensure reliable, affordable and clean energy for its 29 member countries and beyond. The IEA carries out a comprehensive programme of energy co-operation among its member countries, each of which is obliged to hold oil stocks equivalent to 90 days of its net imports. The Agency's aims include the following objectives:

- Secure member countries' access to reliable and ample supplies of all forms of energy; in particular, through maintaining effective emergency response capabilities in case of oil supply disruptions.
- Promote sustainable energy policies that spur economic growth and environmental protection in a global context – particularly in terms of reducing greenhouse-gas emissions that contribute to climate change.
- Improve transparency of international markets through collection and analysis of energy data.
- Support global collaboration on energy technology to secure future energy supplies and mitigate their environmental impact, including through improved energy efficiency and development and deployment of low-carbon technologies.
- Find solutions to global energy challenges through engagement and dialogue with non-member countries, industry, international organisations and other stakeholders.

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The European Commission also participates in the work of the IEA.

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Foreword

The milestone COP21 Paris Agreement recognised the importance of energy technology and innovation in meeting our climate objectives while dictating new climate goals that are more ambitious than ever. The International Energy Agency (IEA) stands ready to provide technology and policy advice to rise to the new challenges our leaders have put before us. This year's edition of *Energy Technology Perspectives* (*ETP 2016*) – marking the 10th anniversary of our flagship publication on energy technologies – showcases the importance the IEA places on supporting clean energy and energy efficiency. Similarly, our Energy Technology Network, which has been running now for more than 40 years and comprises 39 Technology Collaboration Programmes with the participation of more than 6 000 experts worldwide, highlights our commitment to fostering multilateral technology co-operation.

While the accomplishment of COP21 was an important step forward, the focus must now turn to implementation. We need to put actions behind our words to lend credibility to our commitments. We will succeed in this only through greater reliance on partnerships and collaboration. Just as I have emphasised that the IEA has to "open its doors" to the emerging economies if global energy challenges are to be tackled effectively, so must we look at energy technology partnerships at multiple levels, such as between the public and the private sectors as well as among various sectors of the economy and between the different levels of government.

The Paris Climate Agreement was made possible in great part by the realisation that a deal could only work based on a bottom-up approach with proper consideration given to the views of all stakeholders. Thus, the active engagement of cities, civil society and private entities brought confidence that all parties could work together to build a world where human development and environmental responsibility are compatible with economic growth. The importance of cities is clear: they represent almost two-thirds of global primary energy demand and account for 70% of carbon emissions in the energy sector. Recognising the success of COP21, and building on the role of cities as drivers of economic growth and global energy use, *ETP 2016* highlights how national energy policy makers can work with local governments to make cities more efficient, secure and healthy places to live, while also contributing to national and global sustainability objectives.

Our analysis shows that clean energy technologies and policies can indeed meet multiple objectives in the most effective way. For example, sustainable mobility solutions can increase access to services while reducing congestion and increasing productivity. Efficient building technologies can reduce energy investment needs while increasing comfort for residents. Local sources of energy and integrated distribution systems can decrease the costs associated with delivering various services, while improving resiliency and flexibility. Cities can also be drivers of innovation, acting as real-life test-beds where linkages between various technologies, and between technologies and market structures, can be evaluated to create innovative solutions and business models that can be exported to other settings. Through case studies, we demonstrate the various opportunities local and national collaboration can offer, for example, showing how Mexican cities can be key partners to enable the very ambitious energy transition enacted by the Mexican federal government.

Recent years have shown how progress can be achieved, but major challenges lie ahead. With CO_2 emissions stagnating for the second consecutive year in 2015 despite a growing global economy, we now have proof that sustainability and growth can go hand in hand, but the uncertainty associated with lower fossil fuel prices may tempt policy makers to act based on short-term opportunities. I hope that this edition of *Energy Technology Perspectives* will promote a longer-term strategic perspective and that local as well as national governments will take on board the policy advice provided here to make cities strategic drivers of a low-carbon future.

Dr. Fatih Birol
Executive Director
International Energy Agency

Executive Summary

The agreement reached at the 21st Conference of the Parties (COP21) in Paris could prove to be a historic turning point for reversing the currently unsustainable trends in the global energy system, provided that this heightened low-carbon ambition is translated into fast, radical and effective policy action. Even in the context of low fossil fuel prices, policy support for low-carbon technologies should mobilise all levers available to accelerate research, development, demonstration and deployment (RDD&D) to make decarbonisation the preferred development path. Chief among such levers is governments' support for urban energy transitions, a conclusion that is supported by the analysis of *Energy Technology Perspectives 2016* (ETP 2016), which shows the vast number and size of cost-effective, sustainable energy opportunities available in cities. Realising this potential, and the multiple non-climate benefits it presents, will require national and local governments to work together effectively.

COP21 boosted the momentum for accelerating low-carbon technology deployment, but concrete action will need to match ambitions

2015 may prove to be a pivotal year for climate change mitigation because for the first time in history all the world's nations agreed by consensus to implement actions aimed at decarbonisation under a common legally binding framework. The Paris Agreement could prove to be a historic milestone for the global energy sector, sending a strong signal through its aims to peak global emissions as soon as possible and reach net-zero emissions in the second half of this century, as well as to keep the global temperature increase well below 2°C and to pursue efforts to limit it to 1.5°C.

The Paris Agreement was a milestone for implementation. For the first time, non-state actors were invited to be an intrinsic part of the process. Not only were public energy stakeholders included in the process but non-governmental organisations (NGOs), the private sector, and regional and local entities as well. Cities were among the front runners, with their strong role in the lead-up to COP21 through the Lima-Paris Action Agenda as well their support for the Paris Pledge for Action. The need to accelerate low-carbon technology innovation has also received significant attention in international fora, with the newly created Mission Innovation and the Breakthrough Energy Coalition aimed at catalysing investments in transformational technologies to accelerate decarbonisation.

A low fossil fuel price outlook poses both unique opportunities and threats for low-carbon technology deployment. While low fossil fuel prices might slow down clean energy technology deployment, they also present opportunities to better align policies with decarbonisation targets, for instance, by accelerating the roll-out of carbon pricing mechanisms and dismantling costly fossil fuel subsidy programmes. Both oil-exporting and oil-importing countries took advantage of the mid-2014 collapse in oil prices to unroll costly subsidy programmes. Low coal prices offer similar opportunities to reduce subsidies on fuel and electricity prices, but this potential window of opportunity needs to be exploited quickly since the current favourable conditions might not be in place for long.

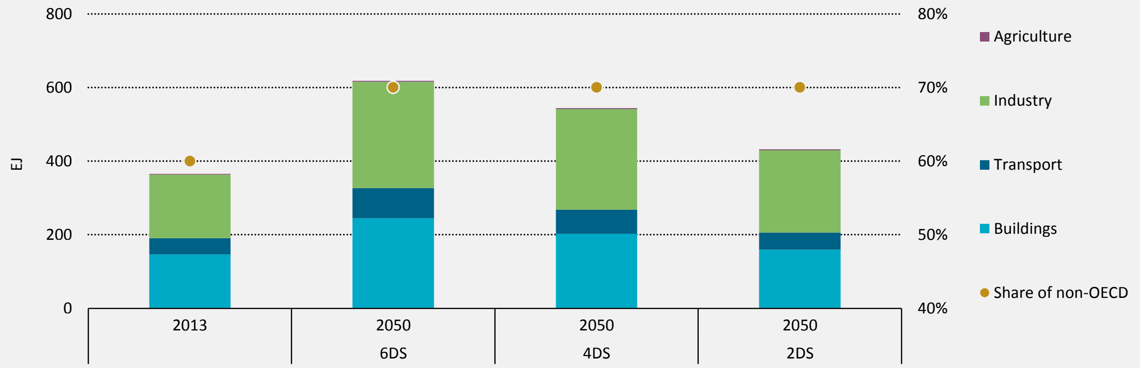
The transition requires massive changes in the energy system, and the 2 Degree Scenario (2DS) highlights targeted measures needed to deploy low-carbon technologies so as to achieve a cost-ef ective transition. With the appropriate policies, such large-scale transformation is realistic and can dramatically reduce both the energy intensity and carbon intensity of the global economy. Compared with a scenario wherein technology deployment is driven only by the policies currently in place (the 6 Degree Scenario [6DS]), in the 2DS, with the right support for low-carbon technologies in conversion processes and end uses, primary energy demand can be reduced by 30% and carbon emissions in the energy system by 70% (and by one-half relative to current levels) by 2050. The two largest contributions to cumulative emissions reductions in the 2DS over the period 2013-50 would come from end-use fuel and electricity efficiency (38%) and renewables (32%). Carbon capture and storage (CCS) would come in third place with 12%, followed by nuclear with 7%.

The investment costs of the 2DS across the power sector and the three end-use sectors (buildings, industry and transport) would not require unreasonable additional financial ef orts from the global economy. Decarbonising the power sector in the 2DS would cost about USD 9 trillion between 2016 and 2050 (equivalent to 0.1% of the cumulative global gross domestic product [GDP] over the same period). Achieving the potential energy savings of the 2DS in the buildings, industry and transport sectors would entail combined additional investment costs of USD 3 trillion between 2016 and 2050. In particular, if the full potential for reduced demand for vehicles and road and parking infrastructure associated with the “avoid” and “shift” options in transport systems is considered, the 2DS in the transport sector could be achieved with lower investment costs than the 6DS.

Cities are at the heart of the decarbonisation effort

The energy landscape is shaped by cities. With more than half of global population and about 80% of the world’s GDP in 2013, cities account for about two-thirds of primary energy demand and 70% of total energy-related carbon dioxide (CO_2) emissions. The energy and carbon footprint of urban areas will increase with urbanisation and the growing economic activity of urban citizens. By 2050, the urban population will grow to two-thirds of global population, and the urban share of global GDP will be about 85%. Continuing current energy system trends, driven by existing policies such as in the 6DS, will increase urban primary energy demand by 70% from 2013 levels to about 620 exajoules (EJ) in 2050 when it will account for 66% of the total (Figure I.1). In parallel, carbon emissions from energy use in cities (including indirect emissions from power and heat generation) would increase by 50%. Hence, efforts aimed at fostering sustainable urban energy paths are crucial to meet national and global low-carbon ambitions.

Figure I.1 Urban primary energy demand in the ETP scenarios, 2013-50



Note: 4DS = 4°C Scenario.

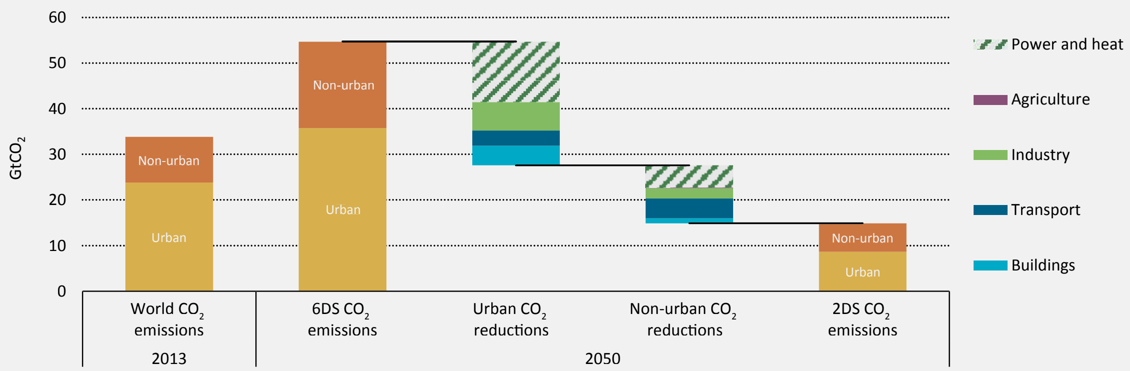
Key point *Under the 2DS, growth in primary energy use attributable to urban areas can be slowed considerably.*

Cities should be at the heart of the sustainable energy transition. The 2DS provides a vision for meeting demand for end-use energy services in cities while at the same time significantly reducing primary energy use and its environmental impacts**.** In fact, cities not only drive energy demand and its environmental impacts; they also offer great opportunities to steer the global energy system towards greater sustainability. Accelerating the deployment of clean energy technologies in the urban environment and supporting behavioural changes among urban citizens can significantly decouple growth in urban primary energy use and carbon emissions from GDP and population growth while ensuring continued access to end-use services. For example, in the 2DS, urban primary energy demand globally can be limited to 430 EJ by 2050 (65% of total primary energy demand), which represents less than a 20% increase from 2013, while urban populations are expected to increase by 67% and GDP by 230% over the same period. Relative to 6DS levels, carbon emissions from urban energy use could be reduced by 75% in 2050. Overall, the potential emissions reduction related to urban energy use by 2050 in the 2DS amounts to 27 gigatonnes (Gt), equivalent to 70% of the total emissions reduction in the 2DS (Figure I.2), which would otherwise not be possible without a transformation of urban energy systems.

Urban energy systems provide significant opportunities for increased efficiency in delivering transport and building services. In the 2DS, final energy demand in the urban buildings and transport sectors in 2050 is reduced by 60% (about 80 EJ) compared with the 6DS. These energy savings can be realised through the avoided "need" for a portion of energy end-use services (e.g. reduced length and frequency of trips in compact cities) and more energy-efficient options to meet the same level of service demand, as in the case of mode shift from personal cars to public transport, walking and cycling. Energy savings and lower-carbon fuels in urban buildings and transport can lead to direct and indirect
(i.e. avoided generation of electricity and heat) carbon emission reductions of about 8 Gt by 2050 in the 2DS (relative to the level achieved in the 6DS) ± which is equivalent to almost two-thirds of the total emissions reduction for these two sectors and to about 40% of the total for all end-use sectors. Key to a significant portion of this urban sustainable energy

potential is increased electrification in end uses (electricity is the largest urban energy carrier in the 2DS by 2050), such as through heat pumps and electric vehicles, coupled with a decarbonised power sector.

Figure I.2 Carbon emissions reductions in the buildings and transport sectors, 2013-50



Key point *Urban areas are key to decarbonising the buildings and transport sectors.*

The way new cities in emerging economies are going to be built is crucial to make the 2DS a reality. In emerging economies, urbanisation can increase access to modern energy services and potentially improve standards of living. In the 6DS, about 90% of the growth in urban primary energy demand (256 EJ) between 2013 and 2050 will take place in cities in non-Organisation for Economic Co-operation and Development (OECD) economies, with even larger shares in the 4DS and 2DS. In parallel, energy-related CO_2 emissions from urban energy use would almost double. However, cities in emerging economies can avoid the lock-in of carbon-intensive urban design characterising many single-use and low-density urban centres in OECD countries while providing access to modern energy services and a wide range of other sustainability benefits to their citizens. In the 2DS, the urban primary energy demand of non-OECD countries grows by about 40% between 2013 and 2050, yet the carbon intensity of their cities is significantly reduced while their urban economies more than quadruple.

Though no one-size-fits-all solution exists to ensure urban energy sustainability, compact and dense urban development is a structural prerequisite to many of the sector-specific options for carbon emissions reduction. The built environment can lock the energy system of a city into either inefficient or sustainable energy-use patterns for decades. For instance, urban form and density can create the premises for reduced demand for mobility and for greater efficiency of energy use in buildings, including the opportunity to integrate low-carbon district heating and cooling networks with heat generated by low-carbon fuels or waste heat from industrial plants. Urban form that incorporates, for instance, mixed-use and public-transport oriented developments, as well as size, density, maturity, economy and the local policy-making capacities of urban areas will heavily influence the appropriate choices of policies and technologies required to meet 2DS goals, but pathways exist to enable sustainable urban energy transitions in all circumstances.

Box I.1 ***ETP 2016*** **country case study: The role of cities in the Mexican sustainable energy transition**

With the official goal of reducing carbon emissions by 50% below 2000 levels by 2050, Mexico has embarked on a very ambitious sustainable energy transition that requires an accelerated low-carbon deployment in all sectors. The 2DS for Mexico shows that this path is achievable with existing or near-commercial technologies and that it can also provide important additional benefits, such as reducing air pollution and traffic congestion. A fast roll-out of a portfolio of technology options will help to reduce CO_2 emissions in the 2DS by more than half by 2050 relative to the 6DS.

The Mexican 2DS is feasible only if local decision makers can step up their efforts to achieve greater sustainability, including reversing urban development patterns that have led to significant sprawl. About 50% of total domestic transport and 75% of buildings final energy demand were associated with cities in 2013. Such demand would obviously grow with demographic and economic drivers, and, under the 6DS, almost doubles from 2013 to 2050. If left unchecked, direct CO_2 emissions from urban buildings and transport will grow in parallel, increasing by 80% between 2013 and 2050 with transport accounting for most of this growth. Tackling the growth of individual transport activity with carbon-intensive fuels is crucial for the feasibility of the Mexican 2DS. Reduced demand for urban mobility, a shift to public transport and deployment of low-carbon vehicles in cities would provide more than 60% of the emission reductions in transport in Mexico in the 2DS relative to the 6DS levels by 2050.

Effective policy action to take advantage of the urban decarbonisation potential would enable Mexico to lock in its urban infrastructure to more sustainable paths that could achieve more efficient energy use for decades. For example, metropolitan areas in hot climates that will experience high demand for social housing could set an example by rolling out sustainable social housing programmes with high-efficiency multi-residential buildings. This strategy would allow for the provision of increased thermal comfort but with limited associated energy costs. In addition, federal and state governments should foster greater co-ordination with municipalities so that unsustainable trends such as urban sprawl are reversed.

Cities can enable unique, cost-effective options and synergies to accelerate the decarbonisation of the buildings sector

Urban buildings today account for about two-thirds of final energy consumption in the buildings sector. Under the 6DS, urban buildings energy consumption will grow by as much as 70% over 2013 levels. If the potential for building energy efficiency options is realised in line with the 2DS, urban buildings final energy consumption could be reduced by more than 30% in 2050 compared with the 6DS. At the same time, annual buildings sector direct CO_2 emissions would be reduced by over 50% compared with 6DS levels. The most important levers to achieve such potential are the construction of high-efficiency new buildings, deep energy renovations of existing buildings, and the deployment of energy-efficient space heating and cooling technologies.

The energy demand of buildings is dominated by space heating and cooling demand in cities, but accelerated deployment of low-carbon technologies could help meet or even improve thermal comfort demand while reducing negative environmental impacts. Representing about 40% of global buildings energy use, space heating and cooling continues to be a critical area of needed action in the buildings sector, especially in cities. In particular, space cooling demand will increase significantly in emerging economies; in the 6DS, by 2050 energy demand for space cooling increases more than fivefold in urban areas in non-OECD economies, with even higher growth rates in a few countries, particularly in India where it increases by a factor of 25.

Cities have several key enabling characteristics that provide additional options for reducing energy use in buildings. The potential greater concentration of households in high-rise buildings can provide for lower energy use to meet the same level of end-use services. In addition, the possibility of connecting to district energy networks can provide urban households with a more cost-effective and less carbon-intensive heating and cooling supply than would be available through individual heating systems. Cities also enable the possibility of developing local expertise to supply energy-efficient buildings technologies as well as the benefits of economies of scale due to the concentration of demand. Technology providers can have market access to a large customer base, and urban communities can spread best practices and customer information faster, accelerating technology diffusion.

Local policy makers have the levers available to drastically shape or reshape the built environment. Local authorities can foster decarbonisation of the urban buildings sector through regulatory land-use planning functions by enforcing buildings codes as well as through planning for efficient, low-carbon or zero-carbon district energy networks. National policies can foster and complement urban low-carbon buildings policies in many ways, including through mechanisms affecting the buildings sector as a whole (e.g. by setting minimum performance standards, fiscal policies, etc.) or, more specifically, for urban buildings by introducing sustainable urban land-use planning frameworks coupled with capacity-building initiatives for local planners.

Gathering information is also essential to understand where to prioritise actions so as to get the biggest return. One prerequisite to enable local planning to achieve greater sustainability of building energy use is understanding trade-offs between different clean energy solutions, such as whether it is more cost-effective to extend an existing district heating network or to pursue deep building energy retrofits. For example, as local planners assess renovation packages for existing buildings stock and determine the point at which deeper renovations are no longer cost-effective, that information will help to guide the effectiveness of buildings policy targets. Capacity for data gathering and analysis is, therefore, crucial to ensure that decisions can be made with a full understanding of the opportunities, challenges and trade-offs among the various solutions.

Urban transport systems can lead the low-carbon transition in mobility

Cities are the main drivers of global mobility demand as a result of direct passenger transport activity within and among urban areas, as well as indirectly through freight activity needed to meet the demand for goods of city residents. Urban transport activities accounted for about 40% of total transport energy use and total well-to-wheel greenhouse gas emissions in 2013. In addition, a significant portion of non-urban transport activity results from the material and product demand of urban businesses and households. Different regional patterns of urban mobility will, in turn, determine the range of options available to increase the energy sustainability of urban transport. For instance, in OECD countries, most urban mobility currently takes place with personal light-duty vehicles, so a shift from personal transport to public transport, walking and cycling is vital to achieve the 2DS in transport. The role of public transport is equally relevant in non-OECD economies to avoid sprawl and the associated high share of personal transport characteristic of some cities of the developed world.

Many opportunities exist in cities to curb transport-related carbon emissions by reducing trips and trip distances, shif ing activity to public transport, and progressively adopting more efficient, low-carbon vehicles. In the 2DS, urban areas can directly deliver nearly half of the energy savings and two-fifths of the emissions reduction of the transport sector compared with the 6DS by 2050. Higher vehicle efficiency and low-carbon fuels are necessary pillars for the decarbonisation of urban transport; together they provide about two-thirds of the emissions reduction potential. “Avoid” and “shift” options in urban areas would deliver 36-39% of the emissions reduction in urban transport (and about 15-16% of the total for transport), which highlights the strategic relevance of urban planning and municipal travel demand management (TDM) policies for the 2DS.

The benefits of less energy- and carbon-intensive urban mobility go beyond the emissions reductions that can be realised in cities. Low-carbon mobility can leverage additional local sustainability benefits such as reduced air pollution, decreased congestion and increased safety. In addition, cities are also important test beds for the penetration of advanced transport technologies such as new mobility concepts like “Mobility as a Service” or the incorporation of information and communication technologies (ICTs) into urban transport (e.g. as a means of integrating public transport services across modes or even with the eventual advent of autonomous vehicles). Moreover, urban driving is well suited for the deployment of battery electric vehicles (BEVs) through conventional ownership models, car-sharing, or dynamic ride-sharing programmes. The urban environment can provide a suitable niche for BEVs due to lower range requirements and the potential availability of a concentrated network of public charging points.

Local policy makers have many levers available to increase the sustainability of urban transport with the appropriate enabling environment. Local authorities should implement TDM measures that support the uptake of non-motorised (cycling, walking) and public transport in parallel with accelerated diffusion of electric vehicles, including electric two-wheelers, public taxi and bus fleets, and light commercial vehicles (for freight deliveries and other municipal services such as waste collection and postal services). Pricing policies (e.g. congestion charging, cordon pricing and tolls), regulatory policies (e.g. access restrictions and registration caps), and investments in and subsidies to public transport and non-motorised mobility are examples of municipal measures that need to be aggressively rolled out to meet the 2DS in urban transport. The potential of local policies to decarbonise urban transport will depend on the ability to leverage national policies that provide the appropriate pricing signals – most importantly strong personal vehicle and fuel taxation regimes – as well as national frameworks that enable sustainable transport planning (and, in particular, transport integrated with land use).

Urban low-carbon energy supply and smart urban energy networks can provide many potential benefits at both the local and national levels

Renewable energy sources located in urban areas can make an important contribution to meeting the energy needs of cities while at the same time increasing urban energy resilience and retaining economic value within urban communities. Among renewable energy sources that can be deployed in urban areas, rooftop solar photovoltaics (PV), municipal solid waste (MSW), and sewage and wastewater gas are often already cost-effective today and can play a relevant role in covering the electricity, heating and cooling needs of cities. Though the potentials from MSW, sewage, and wastewater gas are not large on absolute scales (e.g. equivalent to less than 4% of urban electricity needs in 2050 in the 2DS), these energy resources can provide relevant cost savings for waste and water treatment services provided by cities.

Roof op solar PV can make a significant contribution to meeting electricity demand in cities. The technical potential for rooftop solar PV could provide up to 32% of urban electricity demand and 17% of global total electricity demand in the 2DS by 2050.

Taking into account the competition with alternative generation options, around 5% of the urban electricity needs would be cost-effectively covered by urban rooftop solar PV in 2050 in the 2DS. The urban solar PV potential is larger in small cities, due to their lower density. These small cities, however, are often least prepared for realising this potential. National and regional governments can play a critical role here in supporting cities by addressing the lack of data and limited financial resources and expertise as well as governance capacity.

Cities can decrease the carbon footprint of their thermal demand by reusing excess heat from industrial plants located in the proximity of urban areas. The cost-effectiveness of using industrial excess heat (IEH) in cities depends on local conditions such as the existence of thermal distribution networks and the quality of the heat source among others. The global technical potential of medium- and high-temperature IEH that could be recovered from energy-intensive industries would be equivalent to 2% of current industrial final energy use or to 3% of urban buildings energy use by 2050 in the 2DS. Regionally, cities in developing countries have an important opportunity, since 80% of the identified IEH potential lies in non-OECD economies. To increase IEH recovery, policy frameworks should encourage process integration techniques in industrial sites and foster the mapping of local energy resources and urban demands.

System integration of distributed energy services in cities can allow accelerated penetration of distributed energy sources and peri-urban renewable sources, increasing the resilience and security of both urban and national energy systems. In a global scenario characterised by a high build-up of variable renewables and distributed generation (DG), smarter urban energy infrastructure is an important prerequisite for achieving the 2DS, providing additional non-climate benefits at the national level (Box I.2). The monitoring and control potential from ICT should be incorporated into urban grid planning. In areas with significant heating demand and where much urban infrastructure remains to be built (e.g. China), low-temperature district heating networks can provide a venue for greater system flexibility of national grids.

Box I.2 The benefits of smart urban energy networks for national energy systems

Smart urban energy networks can leverage the combined potential of DG and integrated urban energy grids to provide increased flexibility to the national energy system. Smart, ICT-enabled distributed energy resources (including energy storage) within urban smart energy networks can provide a range of technical services, allowing grid operators to better plan and operate national power systems and, in turn, increase the hosting capacity for renewable and decentralised energy technologies at lower cost.

The benefits of smartening urban energy networks are not confined to power systems: integrating power, heat and fuel networks can increase the utilisation of the system, reduce total costs and offer the national electricity system greater flexibility. For instance, a district heating network can link power and heat production and consumption locally, providing operational flexibility to accommodate periods of excess or scarce variable renewable generation in the national grid. Overall, the greater flexibility provided by such urban power-to-heat systems can not only balance variable renewable generation in the national system but also provide local balancing and other system services to support the integration of distributed energy sources.

By enabling a more distributed system where energy is produced and consumed locally, smarter integrated urban energy grids can reduce the need for investments in national energy infrastructure (including less stringent requirements on reserve capacity or transmission infrastructure). More broadly, they can also enhance energy security through greater redundancy and resilience to external shocks.

New, innovative business models are needed for effective system integration at the urban level. Examples of innovative business models are “micro-grids as a service” or the various existing models that turn consumers into producers and “prosumers”, enabling a wide range of benefits at the local level, including reduced environmental impacts, reduced energy costs for urban communities, increased energy access and greater security of supply. National and local policy makers need to work together to enable these synergies and take advantage of the benefits of smarter urban energy networks, both at the local and national levels (Box I.2).

Mobilising the urban sustainable energy potential requires strong support from national governments to local policy makers

A large part of the potential energy savings and carbon emissions reduction offered by cities will remain untapped unless policy action is stepped up. Early, co-ordinated and effective actions are required to avoid locking in inefficient energy systems; once constructed, buildings, roadways and public transport systems will be in place for many years. The traditional focus of urban energy policies on meeting the energy service demand of urban citizens and, at the same, reducing local environmental impacts has been significantly expanded in the last few years. Many cities have taken on a broader urban sustainable energy challenge. Over the last 25 years, these cities have adopted a strong leadership and pioneering role in addressing new energy sustainability issues such as climate change mitigation and resilience.

The ability of cities to effectively address local energy sustainability issues can translate into increased opportunities to meet national energy policy goals. The capacity of cities to reduce and decarbonise end-use demand as well as to foster urban energy supply is a strategic enabler for national policies. First, smarter urban energy networks can provide for greater flexibility of the broader energy system, which in itself is a pillar for energy security and affordability. Second, reduced air pollution and traffic congestion are translated into lower costs for national health care systems and into increased productivity for national economies. Third, greater urban energy resilience to external shocks such as extreme weather events is also a prerequisite for the strengthened energy security of the national system.

Cities can also be strategic demonstration labs for innovative energy technologies and business models, but engagement from local and national decision makers is crucial to provide the right enabling frameworks for supporting the urban “innovation mine”. Urban energy systems can provide the ideal niches for innovative energy technologies (e.g. electric vehicles, building-integrated PV) to progress from the demonstration phase through deployment to commercial maturity. Accelerated technology diffusion also brings new opportunities as well as needs for new business models. Local and national policies have many levers to support the change spurred by innovative technologies and business models, but the fast pace of such change requires significant flexibility and responsiveness.

Several policy mechanisms that effectively pursue urban energy sustainability are available to local governments. Some of these policy levers can address local energy sustainability from a more holistic perspective. For example, leveraging the role that compact urban forms can play in the global sustainable transition will depend significantly on a strong capacity to implement integrated landuse and transport planning. In addition, sustainable urban energy plans have been widely adopted across thousands of cities around the world. Innovative finance mechanisms (e.g. the Property Assessed Clean Energy mechanism) and governance approaches (e.g. the Sustainable Energy Utility model) have also shown their potential to address many barriers to tapping into the local sustainable energy potential. However, the ambition and effectiveness of these policy approaches are a function of the human, legislative and financial capacity of the municipal administration, which often lacks such capacity even in areas traditionally within its domain such as land-use and transportation planning.

National governments can successfully drive local energy transitions through a combination of enabling frameworks and regulatory approaches. National public decision makers can enable cities to pursue local energy sustainability ambitions in many ways, including: instituting capacity-building programmes for local planners; extending legislative powers on local taxation, land-use and transport planning; and making available dedicated funding schemes for urban infrastructure investments. National policy makers can also introduce mandatory requirements for cities to introduce urban sustainability plans and energy efficiency minimum standards for municipally owned buildings and public transport fleets. Furthermore, in many countries, national fiscal legislation can constrain urban sprawl by setting specific provisions for local land development and use fees as well as property taxes that provide strong financial incentives for compact and dense development.

No single template exists; policy makers need to choose the appropriate mix of successful strategies and solutions according to the specifics of cities and countries. In non-OECD economies, where significant urban infrastructure still needs to be built, a vast opportunity exists for "positive" (low-carbon) lock-in. Capacity building and financial assistance are crucial for cities in emerging economies – and national governments, multilateral development banks, NGOs and international organisations all have a strategic role to play in supporting cities that still have to build significant new energy infrastructure. OECD countries, on the other hand, must work on reducing the carbon footprint of their existing infrastructure – for example, through the retrofitting of commercial and residential buildings and reserving road lanes for bus rapid transit systems. Lastly, another important role for OECD countries is to explore and pilot new financial mechanisms and governance approaches that can generate examples of best practices for emerging economies.

Box I.3 Recommendations to national policy makers

While recommended actions for decision makers in different domains such as government or industry and at different levels (national, local) are provided in each chapter of ETP 2016, the following high-level recommendations aim to summarise the main "entry points" for national policy makers seeking to foster the sustainable energy potential of cities:

- Better alignment of regulatory frameworks with technological innovations will support the uptake of new technologies and innovative business models in urban energy systems.
- The capacity of local governments to implement effective sustainable energy policies should be increased, including extending the legislative power of municipalities where appropriate.
- Extending the ability of cities to generate revenue and access financing at lower cost will support their efforts to undertake sustainable energy programmes and infrastructure projects.
- The ability of local officials to implement integrated land-use and transport planning and sustainable energy planning should be supported through nationally funded capacity-building programmes that, in turn, will greatly benefit from the experience of international organisations.
- Where not already present, establishing institutional clearing houses will enable stronger dialogue and co-ordination between the national and local government levels as well as with other energy stakeholders on such issues as identifying challenges to accelerating urban energy transitions and discussing novel solutions.

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Part 1

Setting the Scene

Part 1 of *Energy Technology Perspectives (ETP) 2016* sets out the International Energy Agency (IEA) vision for the long-term technology paths needed to achieve a sustainable energy system, along with the required policies and the financial investments. In Chapter 1, recent events impacting energy technology deployment and global energy trends are covered in the three main *ETP* scenarios, with analysis across the entire energy sector. Technology-rich modelling of these scenarios to 2050 reveals the possible pathways to a low-carbon energy future, in which ambitious technology deployment is driven by appropriate policy support.

Against the backdrop of the urgent need to transform the way energy is supplied and used to meet climate mitigation goals, Chapter 2 assesses recent progress on clean energy and serves as sixth submission of the IEA to the Clean Energy Ministerial. Offering high-level insights into recent success stories – as well as clear cases of suboptimal deployment – across demand and supply sectors, it acts as a call to action for more effective support from policy makers in all areas where a quick uptake of clean energy technologies is needed for long-term sustainability of the energy system.

Chapter 1 **The Global Outlook** **25**

To achieve a cost-effective transition to a sustainable energy system, a portfolio approach based on different low-carbon energy technologies is needed across supply, transformation and end-use sectors. "The Global Outlook" shows that the sustainable energy transition can be possible with currently deployed or near-commercial technologies, but this will require policy makers to take on the challenge of dramatically accelerating clean energy technology deployment. The impetus gained after the 21st Conference of the Parties will need to be translated into swift and structural policy action, and the low fossil fuel price environment should be a catalyst for reshaping energy policies to meet ambitious climate mitigation goals.

Chapter 2 **Tracking Clean Energy Progress** **77**

Despite low oil prices, investment in renewables and energy efficiency was maintained at a historically high level in 2014 and 2015. Sales of electric vehicles are growing exponentially, while biofuels also had positive developments. Furthermore, the long-term outlook for nuclear power has improved, due to progress and construction times. However, notwithstanding positive developments for some technologies, the broader picture is that the deployment of the majority of technologies will need to significantly accelerate to put the global energy system on track for an impactful low-carbon transition.

Chapter 1

The Global Outlook

To achieve the transition to a low-carbon energy system, stronger, more ambitious policies are required across the energy sector, with further investment critical to accelerate technology development, reduce costs and facilitate deployment. The events of the past year have given fresh impetus to these ambitions. At the 21st Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC), the global energy, financial and business communities pledged to take action. Despite low oil prices, investment in renewables and energy efficiency has been maintained at a historically high level.

Key findings

- ***The link between carbon dioxide (CO_2) emissions and economic growth showed signs of weakening in 2014.*** *For the link to be broken, as it must be for the 2°C Scenario (2DS) to be achieved, improvements in energy efficiency and deployment of low-carbon technologies and fuels must be accelerated. While the rise in deployment of renewables has been impressive, strong growth in the deployment of other clean energy options such as nuclear power and carbon capture and storage (CCS) must follow.*
- ***Primary energy demand continued its growth in 2014.*** *With an 81% share, fossil fuels dominate primary energy demand but the fuel mix is projected to gradually become more balanced in all three ETP scenarios. In the 2DS, renewable energy would reach 44% of primary energy supply in 2050.*
- ***In the 2DS, the power sector is almost completely decarbonised by 2050.*** *Extensive deployment of low-carbon generation leads to a fall in CO_2 intensity of electricity to less than 40 grammes of CO_2 per kilowatt-hour (gCO_2/kWh) in 2050.*
- ***Savings in electricity in the 2DS compared with the 6°C Scenario (6DS) correspond to reduced capacity needs in the power sector.*** *Around 5 100 gigawatts (GW) of new capacity is avoided between 2016 and 2050. The savings of 3.5 trillion United States dollars (USD) correspond to one-fifth of global investments in generation capacity in the 6DS.*
- ***Renewable energy technologies led growth in electricity generation capacity in 2014, accounting for 45% (130 GW) of global net capacity additions.*** *In spite of low oil prices, wind capacity grew by 50 GW and solar photovoltaic (PV) capacity by 41 GW, both reflecting record additions.*
- ***To realise the 2DS, transport emissions need to peak and begin to decline within the next decade.*** *Aggressive policies are required across all modes of transport to meet the 2DS, with strong interventions to promote more sustainable transport modes, vehicle efficiency, and low-carbon fuels.*

- ***Global industrial direct CO_2 emissions peak by 2020 in the 2DS, and are nearly halved compared with the 6DS in 2050.*** *Despite overcapacity in some regions, global industrial activity is expected to grow, increasing the need for near-term action on energy efficiency and research, development, demonstration and deployment (RDD&D) to keep the door open to a low-carbon future.*
- ***In 2050, an estimated 57 exajoules (EJ) could be saved in the buildings sector in the 2DS compared with the 6DS.*** *This is equivalent to the total final energy consumption for nearly all of Africa, the Middle East and the non-OECD Americas in 2013. Around 45% of the savings come from space heating and cooling.*
- ***The climate change agreement negotiated in Paris in December 2015 at COP21 has brought a fresh impetus to global action on climate change mitigation and adaptation.*** *Countries agreed on an objective of keeping the increase in the global average temperature well below 2°C. Following formal adoption of their Nationally Determined Contributions (NDCs), countries will be encouraged to develop and communicate long-term, low-carbon development strategies that would lead global emissions to peak as soon as possible and fall rapidly thereafter.*

Opportunities for policy action

- *While actions to decouple energy demand and economic growth are starting to pay off, efforts to reduce energy-related carbon emissions need to be scaled up significantly. Energy efficiency is an important factor. Investment must increase to grow the energy efficiency market in each of the main energy sectors.*
- *Decarbonising the energy system is the key to decoupling global CO_2 emissions from economic growth. The Paris Agreement achieved at COP21 provides a mandate for policies to be implemented that oblige continued improvements in energy efficiency and further deployment of low-carbon technologies and fuels.*
- *Low oil prices offer prospects to further address energy-price subsidies, where reforms have already led to savings of USD 117 billion over the five years to 2014. The low prices have also led to an estimated USD 380 billion worth of oil and gas projects being cancelled since 2014. Redirecting some part of these funds to renewables and energy efficiency would support the transition to a global low-carbon economy, while providing countries with the resilience to withstand future fuel price volatility.*
- *Whereas ageing infrastructure and high levels of per capita electricity demand characterise many OECD countries, a major challenge for developing and emerging economies is to satisfy growing electricity demand in an environmentally sustainable manner. This creates an opportunity to prioritise deployment of low-carbon technologies, notably renewables, but also CCS, from the outset rather than building unabated fossil fuel plants and running the risk of locking in carbon emissions.*
- *Overconsumption of resources results in environmental degradation and economic losses. Regulations should promote material resource efficiency practices and consider a systematic approach to evaluating the energy and emissions impact of infrastructure investment and manufacturing across the energy sectors.*
- *Working together with key stakeholders, governments in both developed and emerging economies must ensure that consumers and manufacturers maximise the potential for energy efficiency. For example, in OECD countries, deep energy renovations must be promoted in existing buildings. In rapidly emerging economies, high-efficiency new buildings must be constructed over the coming decades, before the bulk of expected stock is built.*

The year 2015 was extraordinary for energy worldwide. The role of technology in providing reliable, affordable and clean energy was underlined, directly and indirectly, by a number of important events. At the United Nations' Third International Conference on Financing for Development, in Addis Ababa, heads of state encouraged countries to consider setting nationally appropriate spending targets for quality investments in essential public services for all, including energy. In New York, the United Nations established the 17 Sustainable Development Goals, with the seventh focused on ensuring access to affordable, reliable, sustainable and modern energy for all. Then came COP21, the stand-out event of the year.

The Paris Agreement, reached on 12 December 2015, was greeted as a landmark by the majority of commentators. The agreement secured an enduring, legally binding treaty on climate action that contains commitments from countries covering 99% of global emissions. It will enter into force in June 2016, provided 55 countries covering 55% of global emissions accede to it.

The main aim of the Paris Agreement was to keep the global average temperature rise this century well below 2°C above pre-industrial levels, while driving efforts to limit the temperature increase to 1.5°C. However, these aims are aspirational for now, with a temperature increase closer to 2.7°C estimated as the more likely outcome of pledges made at COP21 (IEA, 2015a). To meet the longer-term objectives, technology innovation would be a major factor. Under the Paris Agreement, in recognition that the pace of innovation needs to increase, international co-operation to finance, develop and deploy low-carbon technologies was significantly strengthened. Twenty countries came together to launch Mission Innovation (2016), whereby each participating country undertook to double its investment over the next five years to reduce the cost and encourage the deployment of clean energy technologies. In support of Mission Innovation, major players in the private sector agreed to invest, via the Breakthrough Energy Coalition (BEC, 2016), along the technology development chain from the laboratory to the market.

The onset of low oil prices also came in 2015. Having already plummeted from more than USD 115/barrel in June 2014, to under USD 50/barrel in January 2015, prices fell to less than USD 30/barrel in January 2016. However, for a combination of reasons, the decline in oil prices has not led to a significant bounce in demand. Growth in global demand has been modest and is projected to average just 1.2% per year to 2020 (IEA, 2015b). Many oil-exporting economies have been adversely affected. Oil production costs for many of them exceed the market price, while, in others, profits have fallen appreciably. For oil importers, high oil prices from January 2011 to June 2014 prompted investment in renewables (including biofuels) and energy efficiency, with gas and renewables increasingly competitively-priced against oil.

The world's largest economies, the People's Republic of China (hereafter "China") and the United States have both made strides to ensure that efforts to decarbonise their energy sectors are not derailed by cheap oil. China's industrial restructuring and its "war on pollution" have triggered a shift; from being the leading engine of global growth in oil demand, China has become a much less oil-intensive economy. In the United States, fuel economy standards have increased the fuel economy of new vehicles by 25% since 2007 (University of Michigan, 2016), which has more than offset any impact that cheap oil has had on a renewed preference for larger vehicles with higher emissions.

Both oil-exporting and oil-importing countries took advantage of the mid-2014 collapse in oil prices to unwind costly subsidy programmes. The current low coal prices offer similar opportunities to reduce subsidies on fuel and electricity prices. In 2014, fossil fuel subsidies stood at an estimated USD 493 billion; without the reforms adopted since 2009, their value would have been 24% higher at USD 610 billion (IEA, 2015c). However, end users are not seeing as much relief from such reductions as might have been expected and, at the same time, advances in renewables and energy efficiency have made the global economy less fossil fuel-intensive. This, coupled with the diminishing role in the fuel mix of coal and, particularly, oil, has softened the impact of lower prices on demand.

Low oil prices have also led to an estimated USD 380 billion worth of oil and gas projects being cancelled since 2014 (Wood Mackenzie, 2016). Though these decisions and the reductions achieved in fossil fuel subsidies do not necessarily release funds, they may offer opportunities to redirect some additional spend to renewables and energy efficiency, which would support the transition to a global low-carbon economy, while providing countries with some resilience against future fuel price volatility.

The International Energy Agency (IEA) *World Energy Outlook Special Report on Energy and Climate Change* (IEA, 2015a) was launched in October 2015 as an input to the IEA Ministerial Meeting and as a special briefing for COP21. In the special report, the IEA proposed a bridging strategy that could deliver a peak in global energy-related CO_2 emissions by 2020.[1] The bridge scenario depends on five measures, the second and third of which are directly technology-related. The second recommends a progressive reduction in the use of the least-efficient coal-fired power plants and banning their construction. The third proposed increasing investment in renewable energy technologies in the power sector from USD 270 billion in 2014 to USD 400 billion in 2030.

In mid-November 2015, the IEA Ministerial Meeting welcomed ministers and high-level officials from 29 IEA countries and nine partner countries, along with 30 top business executives. At this meeting, the IEA Executive Director, Fatih Birol, laid out three main pillars for modernising the IEA in a transformed global landscape, the third pillar of which was for the agency to become a global hub for clean energy technologies and energy efficiency. To underpin this pillar, the IEA planned to strengthen the role of its Technology Collaboration Programmes, an existing network of 6 000 energy technology experts worldwide. The ministers issued a statement at the end of their meeting calling for a successful outcome at COP21, endorsing the bridging strategy and highlighting the enhanced role of technology in meeting the climate objectives (IEA, 2015d).

The focus on technology is crucial. It is the key to achieving the aggressive changes within the energy sector needed for the world to limit the global average temperature rise to 2°C. *Energy Technology Perspectives 2016* (*ETP 2016*) focuses on a pathway that gives a 50% chance of limiting the global average temperature increase to below 2°C. To identify this pathway and provide the context in which it can be achieved, *ETP* uses three scenarios: the 6DS, the 4˚C Scenario (4DS)[1] and the 2DS (Box 1.1). The 6DS assumes no greenhouse gas (GHG) mitigation efforts beyond policy measures already implemented, leading to a 60% rise in annual energy- and process-related emissions that reach 55 gigatonnes of CO_2 ($GtCO_2$) in 2050. In contrast, CO_2 emissions in the 2DS are reduced to just 15 gigatonnes (Gt) in 2050, less than half the current value. The 2DS is the main focus of *ETP 2016*.

1 Unless stated otherwise, CO_2 values refer to the sum of energy-, feedstock- and process-related CO_2 emissions.

Box 1.1 Scenarios in *ETP 2016*

The *ETP* model comprises four interlinked technology-rich models, one for each of four sectors: energy supply, buildings, industry and transport. Depending on the sector, this modelling framework covers 28 to 39 world regions or countries, over the period 2013 to 2050.

Based on the *ETP* modelling framework, the scenarios are constructed using a combination of forecasting to reflect known trends in the near term and "backcasting" to develop plausible pathways to a desired long-term outcome. The *ETP* scenarios should not be considered as predictions, but as analyses of the impacts and trade-offs of different technology and policy choices, thereby providing a quantitative approach to support decision making in the energy sector. The *ETP* scenarios are complementary to those explored in the *World Energy Outlook* (IEA, 2015c).

The **6DS** is largely an extension of current trends. Primary energy demand and CO_2 emissions (including process and feedstock emissions in industry) would grow by about 60% from 2013 to 2050, with about 1 700 $GtCO_2$ of cumulative emissions. In the absence of efforts to stabilise the atmospheric concentration of GHGs, the average global temperature rise above pre-industrial levels is projected to reach almost 5.5°C in the long term and almost 4°C by the end of this century.

The **4DS** takes into account recent pledges by countries to limit emissions and improve energy efficiency, which help limit the long-term temperature rise to 4°C. In many respects the 4DS is already an ambitious scenario, requiring significant changes in policy and technologies compared with the 6DS. This long-term target also requires substantial additional cuts in emissions after 2050, yet with average temperature likely to rise by almost 3°C by 2100, it is likely to cause serious climate impacts.

The **2DS** is the main focus of *ETP 2016*. It lays out an energy system deployment pathway and an emissions trajectory consistent with at least a 50% chance of limiting the average global temperature increase to 2°C. The 2DS sets the target of cutting CO_2 emissions by almost 60% by 2050 (compared with 2013), reaching a cumulative emissions level of about 1 000 $GtCO_2$ from 2013 to 2050. Carbon emissions from fuel combustion and industrial processes are projected to continue their decline after 2050 until carbon neutrality is reached. The 2DS identifies changes that help ensure a secure and affordable energy system in the long run, while emphasising that transforming the energy sector is vital but not enough on its own. Substantial effort must also be made to reduce GHG emissions in non-energy sectors.

Notes: An extended summary can be found in Annex A. Full descriptions of the scenarios and extensive additional global and regional scenario results can be found online at: www.iea.org/etp.

For the 2DS to be achieved, CO_2 emissions must be decoupled from economic growth, i.e. as economic growth continues, global energy-related CO_2 emissions must fall. Two components must come together to make this happen. Energy demand must be decoupled from economic growth and CO_2 emissions from energy demand.

Efforts to decouple energy demand from economic growth by improving energy efficiency have met with some success. Investments over the last 25 years have led to a steady increase in energy efficiency across each of the main sectors – electricity, industry, transport and buildings. In 2014, the estimate of avoided total final consumption from energy efficiency investments rose to over 520 million tonnes of oil-equivalent or 22 EJ. The energy efficiency market is anticipated to continue to grow, even in the current context of lower oil prices (IEA, 2015e).

The decoupling of CO_2 emissions from primary energy demand has been less successful, but there are signs of movement in the relationship. The energy sector carbon intensity index (ESCII) has held largely stable over the past 25 years. For a combination of reasons, however – such as competition from lower-carbon fuels in the United States and China's extensive energy transformation – evidence has been building that the CO_2 intensity of primary energy demand is losing strength.

Global modelling results

The modelling results from *ETP 2016* analysis reinforce the longstanding message that there is a divergence between where we need to go and where we are headed. The change in direction needed to steer the global energy system away from unsustainable paths will need to be fast and structural.

Primary energy demand

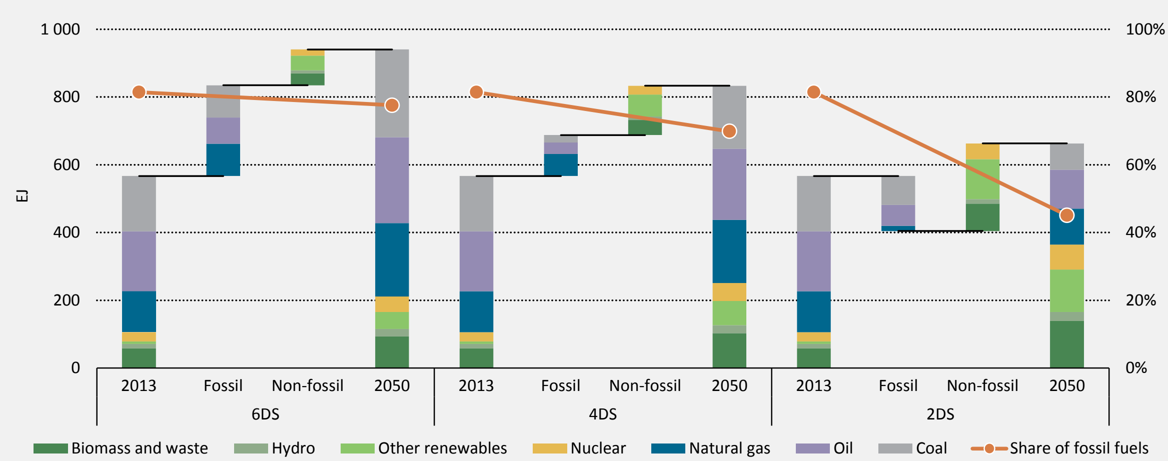
In 2014, global primary energy use lay at 570 EJ,[2] having risen 20% since 2004, and comprised oil (31%), coal (29%), natural gas (21%), biofuels (10%), nuclear (5%) and other renewables (4%). While the share of fossil fuels (81%) has remained stable since 2004, absolute levels of primary fossil energy use rose by about 100 EJ (25%). Energy intensity (the ratio of global total primary energy supply to gross domestic product [GDP]) decreased by about 5% from 2004 to 2014. This indicates that actions to decouple energy demand and economic growth are starting to pay off, but efforts to reduce fossil use and energy-related carbon emissions need to be scaled up significantly.

In the 6DS, primary energy demand reaches 940 EJ by 2050. Fossil fuels still dominate the global energy mix, meeting 77% of primary energy needs (Figure 1.1). Though their share of the total is a few percentage points lower than in 2013, consumption of coal, oil and natural gas in the 6DS would increase by about 270 EJ (58%). The remaining share of the primary energy mix in 2050 is divided among biofuels (10%), other renewables (8%), and nuclear (5%). As a result of continued improvements in the conversion of primary sources and their final uses, the growth rate of primary energy demand in the 6DS gradually decreases over time, so that by 2050, global energy intensity is 50% lower than 2013 levels.

In the 4DS, stepped-up efforts on energy efficiency lead to slower growth in primary energy demand, which by 2050 is 10% (or about 90 EJ) lower than in the 6DS. At about 830 EJ, demand in 2050 is almost 50% higher than 2013 levels. The primary energy mix is still dominated by fossil fuels (70%), followed by biofuels (12%), other renewables (12%) and nuclear (6%). Between 2013 and 2050, absolute consumption increases for each of the three fossil fuels, though the growth in demand for coal is much lower than for oil and natural gas. Demand for primary renewable energy sources more than doubles from 2013 to 2050, with solar PV, wind and biofuels gaining market traction.

2 2014 data on global primary energy supply, final energy demand, and energy-related CO_2 emissions are based on preliminary estimates from the IEA *World Energy Outlook 2015*. These data will be revised following the finalisation of the energy balances for the year 2014. For consistency reasons and unless specified differently, all projections in the three *ETP* scenarios are benchmarked against the modelling baseline year (2013).

Figure 1.1 Global primary energy use in the three *ETP* scenarios, 2013-50



Key point *The primary fuel mix in the 2DS is more balanced across different sources.*

Under the 2DS, primary energy demand totals 663 EJ by 2050, about 30% less than the level projected in the 6DS. Such a reduction is possible with an average annual rate of growth of about 0.5%, almost three times lower than in the 6DS. The fuel mix in the 2DS is radically different from current levels, with the share of renewables (44%) almost equalling that of fossil fuels (45%), and nuclear playing a more significant role (11%). Assuming the same levels of GDP growth in the 6DS and the 2DS, the 2DS requires a decrease in energy intensity of almost two-thirds from 2013 to 2050, an additional 30% reduction from what is achieved in the 6DS.

Final energy demand

Final energy demand totalled about 390 EJ in 2014, with oil being the dominant vector in final uses (39%), followed by electricity (18%), coal (15%), natural gas (15%), biofuels (11%) and heat (3%). Recent trends highlight increased shares of coal (due to the sustained growth in its use in the industry sector) and electricity (largely in buildings), and a lower share of oil.

In the 6DS, final energy demand reaches 667 EJ in 2050, an increase of almost two-thirds on 2013 levels. Oil is still the dominant carrier in 2050, with a 37% share. Electricity shows the largest increase among all vectors, tripling in absolute consumption to reach 24% of final use. Natural gas consumption doubles and its share increases by a few percentage points.

The effects of greater efforts to decarbonise the economy, which are embedded in the 4DS, are reflected in lower final energy demand than in the 6DS, reaching about 590 EJ by 2050. The total share of fossil fuels in final use (62%) in 2050 is only slightly lower than in the 6DS (65%), and their consumption in absolute levels increases by 96 EJ from 2013.

The 2DS presents a radically different picture. Final energy demand still grows, but at a much slower pace than in the 6DS and 4DS, reaching 455 EJ by 2050. The increased consumption in the scenario time frame (about 15% from 2013 levels) illustrates markedly different paths in industrialised countries from those in emerging economies, with industrialised countries exhibiting a much earlier peak in absolute consumption in all *ETP* scenarios. However, even many emerging economies will need to reach their peak in final energy use before 2050 to meet the 2DS.

Overall, the weight of the different carriers in the final energy mix is much more balanced in the 2DS, with potential benefits for energy security. By 2050 electricity surpasses oil in the role of most important carrier, with a share of 28%. However, the growth in absolute levels of electricity (+80%) is less pronounced than in the 6DS. The remaining share is divided mostly among oil (25%), natural gas (16%), biofuels and waste (15%), and coal (11%).

CO_2 emissions

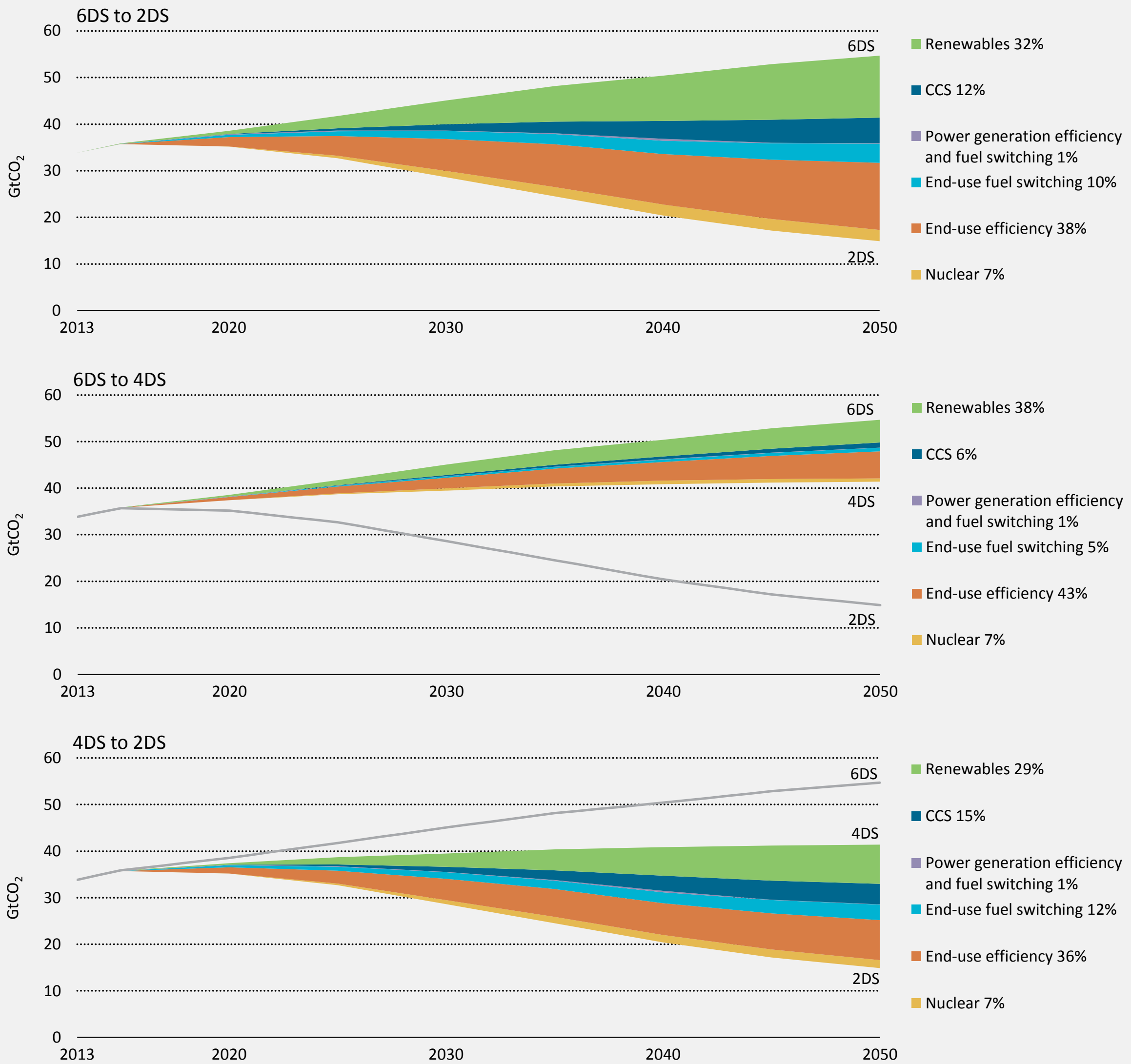
At about 32 Gt, global energy-related CO_2 emissions were still increasing in 2014, having risen by about one-quarter since 2004. CO_2 emissions in 2014[3] were mainly from four conversion and end-use sectors: power (38%), industry (26%), transport (21%) and buildings (8%). If emissions from power generation are allocated to the end-use sectors, the shares of buildings and industry would rise significantly – to around 30% and 40% of the total, respectively.

In the 6DS, emissions reach 55 $GtCO_2$ by 2050, an increase of almost two-thirds over 2013 levels. The shares of the different sectors in total emissions do not change significantly over the 2013-50 timeframe in this baseline scenario. Emissions in the 4DS would increase by about 20% from 2013, reaching 41 $GtCO_2$ by 2050. In contrast, the 2DS requires emissions to be cut by more than half relative to 2013, and by almost 70% compared with the 6DS.

A portfolio of low-carbon technologies is needed to reach the 2DS cost-effectively. Some technology solutions encompass different sectors (e.g. renewables in power and transport); others are almost exclusively relevant to one sector (e.g. nuclear for power). The two largest contributions to cumulative emissions reductions from the 6DS to the 2DS over the period 2015-50 come from end-use fuel and electricity efficiency (38%) and renewables (32%). CCS contributes to 12% and nuclear to 7% of cumulative carbon emissions reductions. The contributions of the different technologies change in relation to the magnitude of the low-carbon ambition. Renewables and end-use fuel and electricity efficiency play a bigger role in the transition from the 6DS to the 4DS, whereas CCS and end-use fuel switching have a more significant contribution to transition from a 4DS baseline to the 2DS (Figure 1.2).

3 Direct emissions refer to CO_2 emissions from fuel combustion in a sector; indirect emissions refer to upstream emissions from the end-use sectors occurring in the power and fuel transformation sectors i.e. allocating the emissions linked to electricity and heat generation to the end-use sectors based on their electricity and heat consumption. Process CO_2 emissions (CO_2 emissions that are inherently generated in a process, for example, from calcination of limestone in cement kilns) are excluded in the 2014 estimate.

Figure 1.2 Global CO_2 reductions by technology area, 2013-50

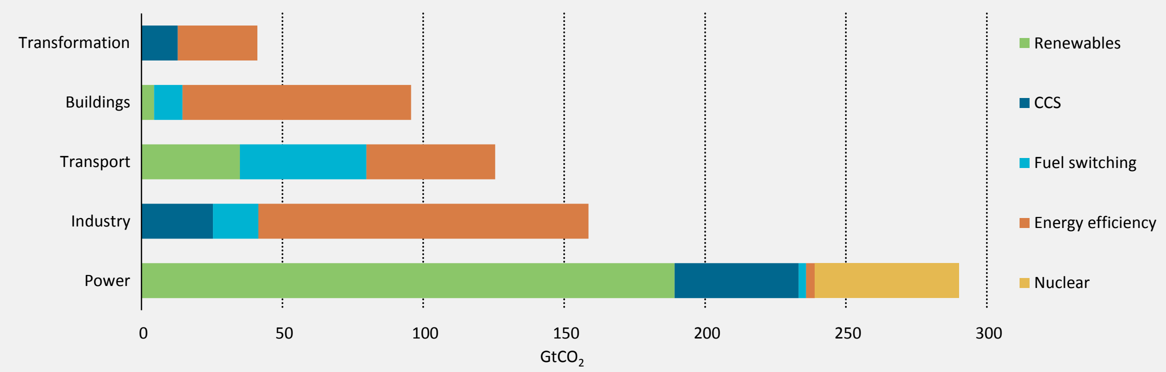


Notes: Percentage numbers represent cumulative contributions to emissions reduction relative to the 6DS. End-use fuel and electricity efficiency includes emissions reduction from efficiency improvements in end-use sectors (buildings, industry and transport), and in end-use fuels (including electricity). End-use fuel switching includes emissions reductions from changes in the fuel mix of the end-use sectors by switching from fossil fuels to other end-use fuels (excluding renewables; fuel switching to renewables is balanced under the category Renewables). Renewables includes emissions reduction from increased use of renewable energy in all sectors (electricity, fuel transformation and end-use sectors). Power generation efficiency and fuel switching includes reductions from efficiency improvements in fossil electricity, co-generation[4] and heat plants as well as from changes in the input fuel mix of the power sector from fossil fuels to less carbon-intensive fossil fuels (e.g. from coal to gas). Reductions from increased use of renewables or nuclear in the power sector are not included here, but accounted for under the corresponding categories. CCS includes emissions reduction from the use of CCS in electricity generation, fuel transformation and industry. Nuclear includes emissions reduction from increased use of nuclear energy in the power sector.

Key point *Achieving the 2DS requires a portfolio approach across all sectors and technologies.*

4 Co-generation refers to the combined production of heat and power.

Figure 1.3 Global cumulative CO_2 reductions in the 2DS compared with the 6DS by sector, 2013-50

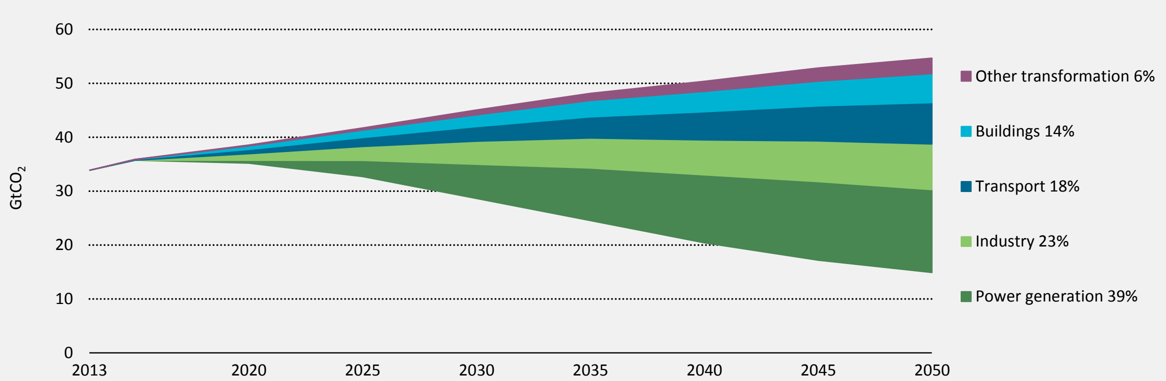


Key point *Actions need to be pursued by stakeholders in all sectors to achieve an optimal transition strategy.*

Sector development in the future energy system

Achieving the magnitude of cuts in GHG emissions needed to realise the 2DS requires major action on both the supply side and the demand side in broadly equal measure (Figure 1.4).

Figure 1.4 Global CO_2 reductions between the 6DS and 2DS by sector



Key point *The 2DS requires significant carbon emissions reductions to be achieved in all end-use and transformation sectors.*

Importantly, in targeting a least-cost pathway, *ETP* modelling and analysis does not depend on the appearance of breakthrough technologies, rather technology options employed are either already commercially available or at a stage of development that makes commercial-scale deployment possible within the scenario period. However, technology innovation is essential, for example, in accelerating technology development, reducing technology costs or facilitating market access. This section considers the potential for a transformation of the global energy system and the role of technologies in achieving the 2DS across four key sectors: electricity generation, transport, industry and buildings.

Electricity generation

Current status

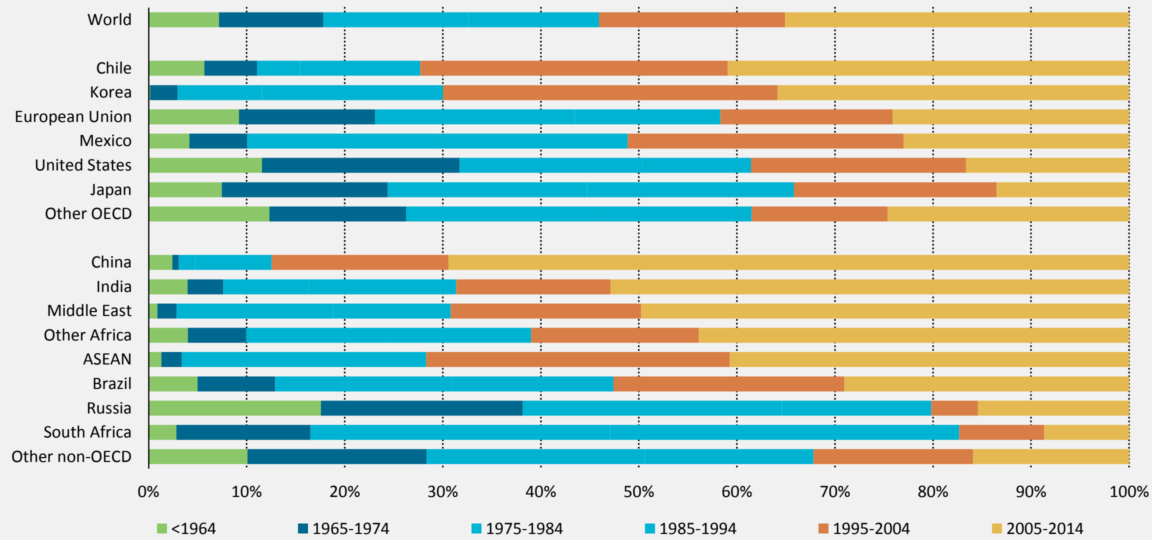
The power sector was responsible for 37% of global primary energy use and more than 40% of CO_2 emissions in 2013. Electricity generation on a global level grew by 3.1% in 2013, with Asian countries accounting for more than 80% of the growth (and China alone for 65% of global growth). Electricity is the fastest-growing carrier of final energy consumed in the industry, buildings, transport and agriculture sectors, with an annual growth rate of 3.3% in 2013, ahead of final energy consumption for coal, oil, gas and renewables.

Renewable energy technologies led growth in electricity generation capacity in 2014, accounting for 45% (130 GW) of global net capacity additions. Wind capacity grew by 50 GW and solar PV by 41 GW, both reflecting record additions despite the low oil prices. In spite of this rapid growth in renewables, the global electricity generation capacity of 5 800 GW in 2014 was still dominated by fossil fuels, with coal representing 33%, gas 27% and oil 8% of installed capacity, whereas renewables accounted for 25% and nuclear 7%.

On a regional level, since 2012, China has been the country with the largest installed power capacity, which has increased by 14% since then to reach 1 245 GW in 2014, or 21% of global capacity, slightly ahead of the United States (20%). The age structure of the power plants in these two countries differed drastically, however: in China almost 70% of installed capacity (865 GW) was built within the last decade, whereas in the United States half of the fleet (580 GW) was over 30 years old (Figure 1.5). Rapid economic growth and the need for more electricity have also led to massive capacity additions in other countries in Asia and the Middle East over the last ten years. India doubled its installed capacity over the last decade. China accounted for more than 40% of global new capacity additions over the last decade, largely in the form of coal plants. The European Union (EU) and the United States were each responsible for around 10% of global new capacity over that period, which mainly consisted of gas-fired and renewable plants.

The differences in the age structure of power plants illustrate the different challenges countries face in decarbonising the power sector. Where demand growth is limited and the generation capacity is ageing, such as in the United States or the European Union, the main challenge is gradually replacing existing plants with variable renewables. Growing economies in Asia and the Middle East must meet a growing demand for electricity, not only resulting in technical challenges to expand the infrastructure, but also requiring financing and trained personnel. This creates an opportunity to deploy low-carbon technologies from the outset, avoiding the lock-in of carbon-intensive infrastructure that occurs if fossil fuel power plants are deployed.

Figure 1.5 Age structure of existing power capacity by region, 2014



Note: ASEAN = Association of Southeast Asian Nations.
Source: Platts (2015), *World Electric Power Plant (WEPP) Database*.

Key point *Age structure of the power generation capacity today differs drastically across regions, from an average age of 9 years in China to more than 30 years in Russia and the United States.*

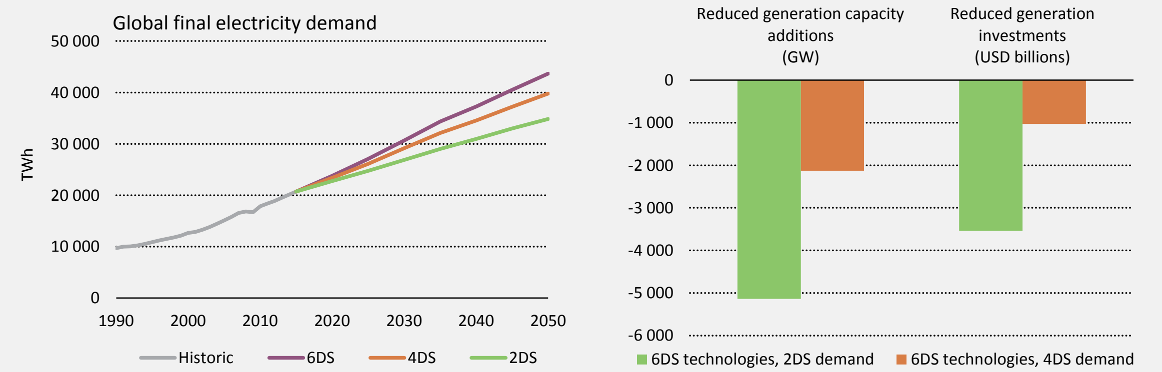
Scenario results

Global final electricity demand more than doubles between 2013 and 2050 in the 6DS (124%) and 4DS (104%). In the 2DS, electricity demand increases by only 79%, due in large part to the increased efficiency of electric end-use services and the replacement of electricity, e.g. of electric water heaters by solar thermal systems in the buildings sector (Figure 1.6).[5] The savings in electricity in the 2DS correspond to reduced capacity needs in the power sector, avoiding new capacity additions of around 5 100 GW in the period 2016-50 and resulting in savings of USD 3.5 trillion, corresponding to one-fifth of the global investments in generation capacity in the 6DS. In the 4DS these savings are smaller, but still amount to reduced capacity needs of 2 100 GW, corresponding to investment savings of USD 1 trillion.

Despite the lower electricity demand in the 2DS, the electrification of energy services in the end-use sectors (e.g. heat pumps in the buildings sector or electric vehicles [EVs] in transport) leads to an increase of electricity in the global final energy mix from 18% today to 28% in 2050. In absolute terms, electricity becomes the largest final energy carrier, with a consumption of 125 EJ in 2050, ahead of oil (113 EJ) and gas (74 EJ).

5 The impacts of the reduced final electricity demand on the electricity sector have been analysed by running variants of the 4DS and 6DS, which assume the final electricity demand as in the 2DS. The reduced capacity needs are therefore based on the 6DS conditions, and should not be confused with the difference in new capacity additions between the 6DS and 2DS, which is strongly influenced by the transition to low-carbon technologies in the 2DS with different full-load hours than the dominantly fossil technologies in the 6DS.

Figure 1.6 Impacts of end-use electricity savings in the 4DS and 2DS compared with the 6DS, 2015-50

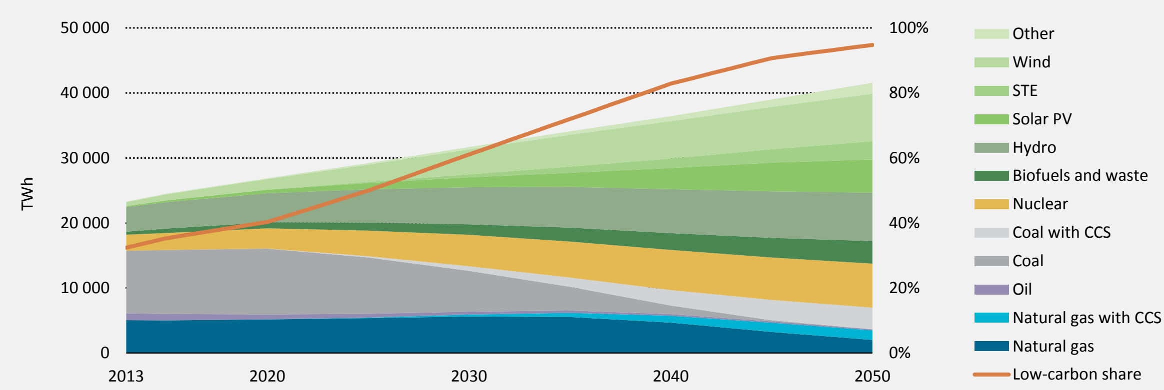


Source: IEA analysis and IEA (2015f), *World Energy Statistics and Balances*, www.iea.org/statistics.

Key point *Electricity savings in the end-use sectors not only reduce electricity bills for consumers, but also provide investment savings in the power sector.*

In the 2DS, global electricity generation is almost completely decarbonised by 2050, with the CO_2 intensity of electricity falling from 528 gCO_2/kWh in 2013 to less than 40 gCO_2/kWh in 2050. This is achieved by extensively deploying low-carbon generation options. At the global level, the share of renewables in the generation mix increases from 22% in 2013 to 67% by 2050 (Figure 1.7). Coal- and gas-fired power plants equipped with CCS reach 12% of generation in 2050, and the share of nuclear increases from 11% to 16%.

Figure 1.7 Global electricity generation mix in the 2DS, 2013-50



Notes: STE = solar thermal electricity. Low-carbon share refers to the combined share of the generation of electricity from renewables, nuclear and CCS.
Source: IEA analysis and IEA (2015f), *World Energy Statistics and Balances*, www.iea.org/statistics.

Key point *Today fossil fuels dominate electricity generation with 68% of the generation mix; by 2050 in the 2DS, renewables reach a similar share of 67%.*

Globally, the integration of a growing share of electricity from variable renewable sources (30% by 2050 from solar PV and wind) requires increased flexibility in the electricity system. Flexible power plants on the generation side, such as combined-cycle and open-cycle gas turbines, can facilitate increased generation from variable renewables. In the 2DS, the full load hours of gas-fired capacity more than halve, from 3 300 hours in 2013 to 1 250 hours in 2050, as gas power plants are used more and more to balance generation from variable sources. Storage can also shift generation from variable renewables from times of excess supply to times of high demand. In the 2DS, the global storage capacity, mostly pumped storage, more than triples to 560 GW by 2050. Like storage, demand response moves electricity demand to times of surplus electricity supply. Already today's electricity uses in buildings (e.g. air conditioning) and industry provide opportunities for increased flexibility through demand response. The prerequisite is smarter control and operation of electric services, e.g. through smart meters. The transport sector could also provide opportunities for demand response. In the 2DS, around 500 million EVs in 2050 are assumed to be available for smart charging, with an annual electricity demand of 450 TWh. Extending the geographic area for balancing electricity supply sources and demand centres through transmission lines is a further option to improve flexibility, but has not been included in the global scenarios, though the role of transmission is discussed in more detail for the five Nordic countries in *Nordic Energy Technology Perspectives 2016* (Box 1.9).

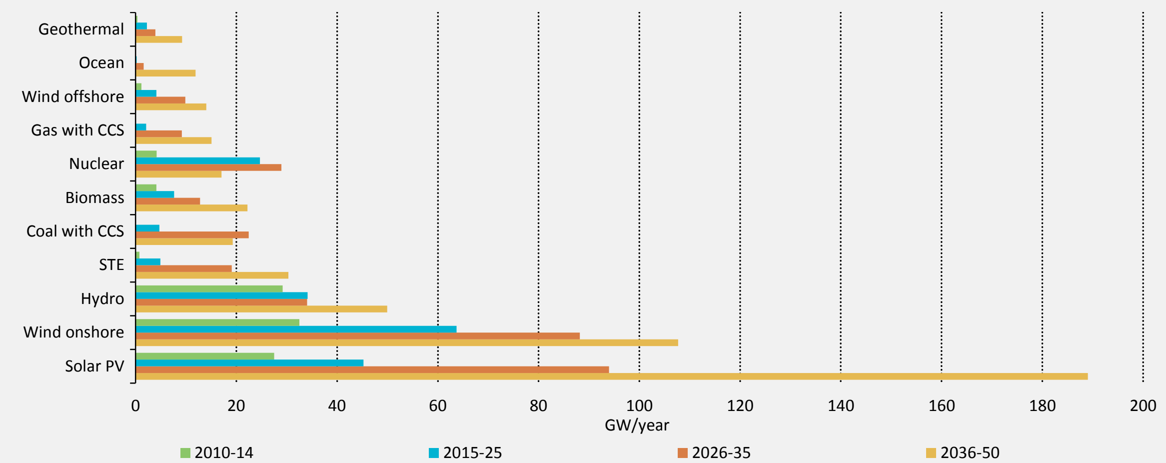
A further challenge to decarbonise the electricity system is to accelerate the deployment of low-carbon technologies for generation (Figure 1.8). With the exception of hydropower, the deployment rate of all low-carbon technologies needs to accelerate over the next 35 years. The highest deployment rates are needed for solar PV and onshore wind. For solar PV, for example, the deployment rate has to almost double from 27.5 GW per year (GW/yr) between 2010 and 2014 to 45 GW/yr between 2015 and 2025, a rate that according to preliminary data has already been exceeded for 2015. A further doubling to 94 GW/yr is needed for the decade from 2026 to 2035 and almost a further doubling to 189 GW/yr from 2036 to 2050. Not all of the PV capacity deployment between 2036 and 2050 increases installed capacity, as one-third of the deployment is needed to replace existing PV panels that have reached the end of their technical lifetime.

Such accelerations in deployment rates for low-carbon technologies are challenging, but not unprecedented: annual solar PV capacity additions were on average 4 GW/yr from 2005 to 2009, but grew to 27.6 GW/yr between 2010 and 2014. By supporting research and development (R&D) of alternative materials, governments can reduce the dependency on specific materials or production processes. Stable policy frameworks and targets for low-carbon technology deployment can also stimulate innovation in industry. Predictable policies are crucial in providing the confidence needed for investments in manufacturing facilities.

A large, skilled workforce will be needed to develop low-carbon power generation technologies, build manufacturing plants and install, operate and maintain the plants. For the wind industry, a work force of around 1.4 million people would be needed in 2025 to reach wind deployment rates similar to those in the 2DS for the decade between 2015 and 2025 (67 GW/yr for onshore and offshore combined) (Lehner et al., 2012). Governments could help establish the necessary education and training activities, though competition for skilled engineers and technical staff with other industries may become a potential bottleneck.

To realise the 2DS, the lock-in of carbon-intensive technologies in the power sector needs to be avoided. Given the technical lifetimes of the coal power plants currently operating or under construction, around 1 200 GW could still be operating in 2050. This capacity corresponds to almost two-thirds of the global coal power capacity in 2013 and would emit around 5.4 $GtCO_2$ annually – more than three times the 2DS power sector emissions of 1.4 $GtCO_2$ in 2050. Clearly, in this scenario, early retirement of coal capacity or retrofits with CCS are unavoidable. If new coal capacity is not equipped with CCS from the outset, it should be designed with future CCS retrofitting in mind, taking into account space requirements for capture-related equipment and proximity to CO_2 storage potential.

Figure 1.8 Global deployment rates for low-carbon power technologies in the 2DS



Note: Hydro includes pumped storage.
Source: IEA analysis and IEA (2015g), *Medium-Term Renewable Energy Market Report*, http://dx.doi.org/10.1787/23070293; IAEA (2016), *Power Reactor Information System* (database); Platts (2015), *World Electric Power Plant* (WEPP).

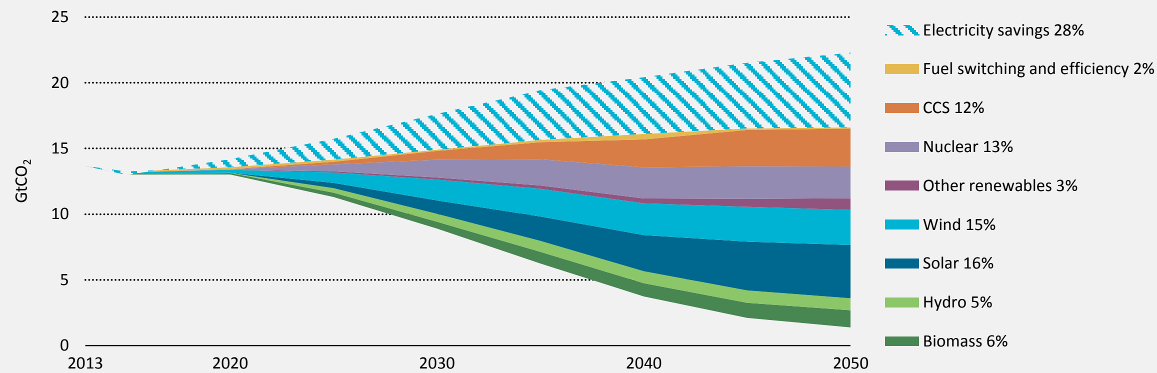
Key point *The deployment rate for new capacity of almost all low-carbon power technologies (except hydro) needs to accelerate in the 2DS compared with current rates.*

Electricity savings in end-use sectors not only reduce the capacity and investment needs (Figure 1.9), but also reduce total CO_2 emissions in the power sector. More than one-quarter of the global cumulative CO_2 reductions for the period 2016-50 in the 2DS compared with the 6DS are met through electricity savings in the end-use sectors (Figure 1.8).[6] These demand-side measures alone could lead to a stabilisation of global CO_2 emissions from the power sector at an annual level of around 16 $GtCO_2$. To reach global power sector emissions of around 1.4 $GtCO_2$ by 2050, however, further efforts in the power sector itself are needed, with contributions from renewables, CCS and nuclear. Renewables contribute 45% to the cumulative emissions reduction. CCS provides 12%, capturing around 3.5 $GtCO_2$ worldwide in 2050, representing roughly half of the total annual CO_2 captured.[7] Nuclear energy accounts for 13% of the emissions reduction in the power sector, with global nuclear capacity more than doubling to 914 GW in the 2DS.

6 The electricity savings shown in Figure 1.8 are the net impact of two opposing effects on the electricity demand side: more efficient use or substitution measures reduce electricity demand (e.g. replacing electric water heaters with solar thermal ones), whereas electrification of some end-use services (e.g. heat pumps, EVs) has an increasing effect. Overall, the former effect dominates, leading in 2050 to a 20% lower final electricity demand in the 2DS compared with the 6DS.

7 CO_2 is not captured only in the power sector in the 2DS, but also at industrial production sites and at fuel production plants. In total, 6.4 $GtCO_2$ are captured in 2050 in the 2DS globally.

Figure 1.9 Key technologies to reduce power sector CO_2 emissions in the 2DS compared with the 6DS



Note: Percentage numbers refer to the contribution of the technology area to the cumulative CO_2 reduction in the 2DS compared with the 6DS over the period 2016-50.
Source: IEA analysis and IEA (2015h), *CO_2 Emissions from Fuel Combustion* (database), www.iea.org/statistics.

Key point *Electricity savings in the end-use sectors would stabilise power sector emissions; to realise the 2DS, a portfolio of low-carbon generation technologies is needed to sufficiently decarbonise electricity.*

Power investment needs

Decarbonising power in the 2DS requires total cumulative investments of USD 37.2 trillion over the period 2016-50, while in the 6DS cumulative investment needs, at USD 28.3 trillion, are around 24% lower.[8] These investments include costs for generation of electricity and heat as well as for transmission and distribution (T&D) and storage.

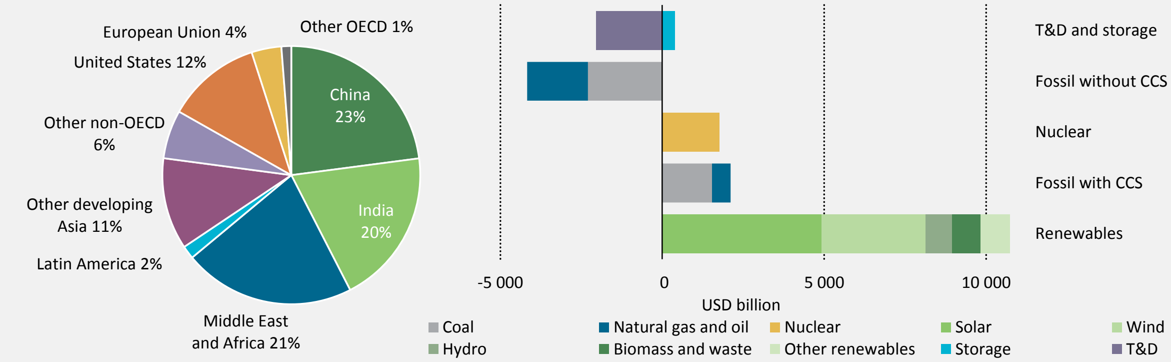
On a regional level, the major part (85%) of the additional investment is required in non-OECD countries, notably China (22%) and India (21%), due to their strong growth in electricity demand of 140% between 2013 and 2050 (Figure 1.10). On a technology level, renewables combined, at USD 10.7 trillion, account for the lion's share of the additional investments, followed by CCS (USD 2.1 trillion) and nuclear (USD 1.8 trillion). These additional investment needs are partly offset by reduced investments in fossil power plants without CCS of USD 4.2 trillion as well as – due to lower electricity demand in the 2DS – reduced investments in transmission and distribution infrastructure of USD 2.1 trillion (compared with the 6DS).

Key actions

The electricity system plays a central role in the pathway to a low-carbon energy future. The power sector is the largest carbon-emitting sector in many countries, so its decarbonisation is crucial for deep cuts in emissions. Low-carbon electricity can also replace fossil fuels in the end-use sectors, e.g. through electrification of transport or heating. Action is needed in various parts of the electricity system: on the generation side; in the interface between electricity supply and demand, i.e. the operation of the electricity system; and on the demand side.

8 Unless specified differently, all USD figures are in purchasing power parity (PPP) constant 2014 terms.

Figure 1.10 Additional investment needs in the power sector by region and by technology



Key point *More than 40% of the additional investments in the power sector are needed in China and India; on the technology side, renewables dominate the investment requirements.*

On the electricity generation side, opportunities and challenges differ among countries. In many OECD countries, where infrastructure is ageing and levels of per capita electricity demand are saturated, special attention has to be paid to integrating a growing share of variable renewable generation. In emerging and developing countries, the need to satisfy growing electricity demand offers an opportunity to deploy low-carbon technologies from the outset.

Financing low-carbon electricity technologies, which are often capital-intensive, will be a challenge in both groups of countries. In saturated markets, low electricity prices provide insufficient revenues to make investments in low-carbon alternatives attractive; in emerging and developing countries, access to capital and costs of financing can be a major hurdle. Governments can intervene in various ways to overcome these barriers, from technology-specific support, such as RD&D, to market regulations and carbon pricing.[9]

Rapid deployment of low-carbon generation technologies, as envisioned globally in the 2DS, can pose supply-chain challenges. Governments can intervene in various areas to address potential bottlenecks. Stable policy frameworks are a pre-condition for long-term investments to avoid supply-demand imbalances in materials or technology components. Targeted R&D in alternatives may help to reduce dependency on materials, which can be a critical obstacle to the ramp-up of technology deployment. Engineers and technical staff will be needed to develop, build and operate the low-carbon power generation technologies. Governments can take an active role in adjusting university curricula and training activities.

In addition to the extensive deployment of low-carbon technologies, the early retirement of coal-fired power plants before the end of their technical lifetime is indispensable to realise the 2DS. Generation from the least-efficient coal-fired power technology ("subcritical" plants) needs to be progressively reduced by eliminating further construction and by running existing plants or those under construction only long enough to cover electricity needs and ensure system security (IEA, 2015a). Newer, more efficient coal-fired power plants should be capable of being retrofitted with CCS.

9 A detailed discussion of market and investment aspects of decarbonising the power sector can be found in *Re-powering Electricity Markets* (IEA, 2016).

On the electricity system side, incorporating a higher share of variable renewables and supporting the electrification of end-use sectors will require a more flexible electricity system. Integrated energy system planning can help to identify the appropriate mix of the four main flexibility measures within a given electricity system (flexible generation, electricity storage, interconnectors and demand response) and the possible balancing options external to the electricity system, e.g. district heating systems or fuel production. Policy makers can support the planning process by conducting integrated energy system studies and providing guidance to the different actors in the system, following up with assistance at implementation and regulatory levels. Existing regulatory and market frameworks often fail to properly value the system-wide flexibility benefits of certain technology options, both within and outside the electricity system. Regulations and market conditions should be adapted to enable new business models that make such system services economically viable.

On the electricity demand side, increasing the efficient use of electricity can help to reduce investments both in generation and at the system level to decarbonise the electricity system. Investigating opportunities to avoid the unnecessary use of electricity and to improve the efficiency of remaining generation should be a first step in any effort to reduce emissions in the electricity system. The extra costs of more efficient technologies on the end-use side are often more than made up by savings in investments in generation or in T&D.

Transport

Current status

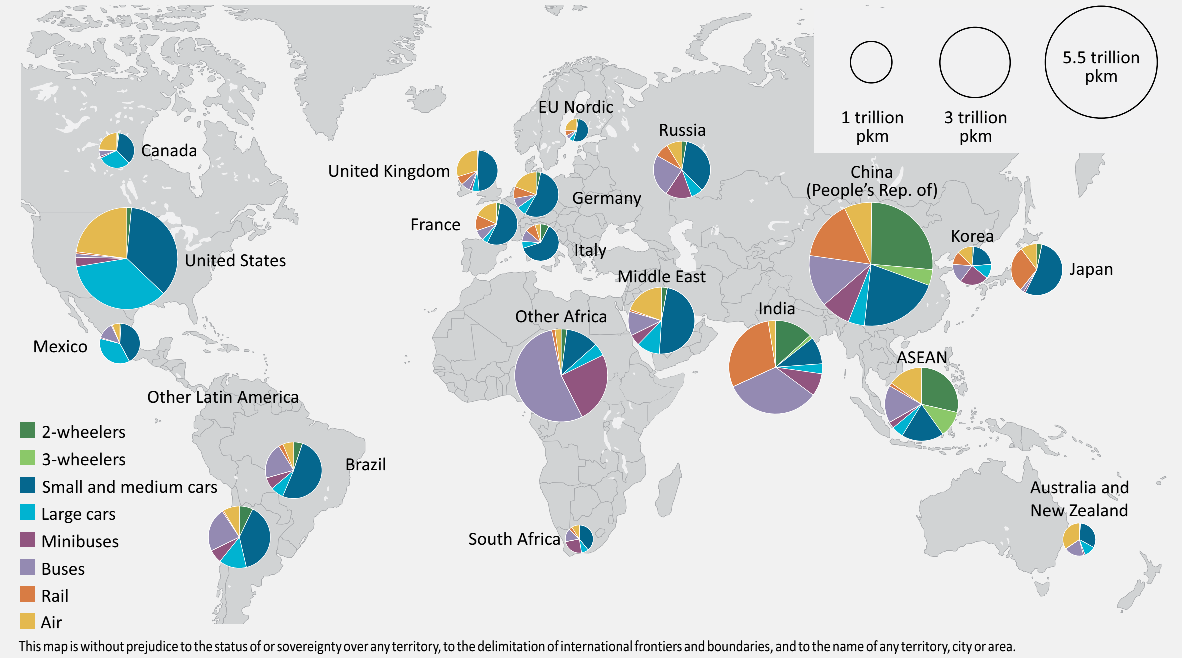
In 2013, transport accounted for 103 EJ or 26% of final energy demand and 7.3 $GtCO_2$ or 21% of global energy-related CO_2 emissions. The rate of growth in transport emissions closely tracks energy demand. Though emissions continue to increase, growth slackened to less than 2% per year between 2006 and 2015,[10] down from more than 2.5% per year over the previous ten years. Achieving the 2DS will require that transport emissions peak and begin to decline within the next ten years, and this will require considerably faster improvements than historic rates.

The evolution of transport energy demand and GHG emissions depends on changes in transport activity, shares of activity in different transport modes, the energy efficiency of each mode, and the carbon content of fuels. Differing characteristics of urban and non-urban mobility also shape the trajectory of energy and emissions from transport (see Chapter 5, which focuses on urban transport trends).

Passenger transport. Personal modes dominate passenger travel, particularly in countries with high incomes and low fuel taxes (Figure 1.11). Canada, Mexico and the United States have high shares of passenger activity in cars (in passenger-kilometres [pkm]) and high ownership of large cars. Car travel is also prevalent in European and Asian OECD countries (though car fleets in these regions are comparatively small and efficient) and in the Middle East and, to a lesser extent, in Japan and Russia. In China, India and member countries of ASEAN, personal 2- and 3-wheelers account for high shares of passenger travel.

10 The analysis was conducted with 2015 as the base year, as the IEA Mobility Model runs on five-year time steps from 1975 to 2050. Readers should note that all values for 2015 are extrapolated based on historic data from time series that extend through 2013.

Figure 1.11 Passenger transport activity in the main global regions, 2015



Note: The year 2015 is taken as the base year of the analysis conducted here, but readers should note that all values for 2015 are extrapolated based on historic data from time series that extend through 2013.

Key point *Motorised transport activity varies greatly in magnitude and modal composition across regions.*

In developing regions, where average income and car ownership levels are lower, more travel occurs by public transport (bus and rail). Rail activity varies greatly among non-OECD economies. While Latin America, Africa and ASEAN countries rely primarily on bus, rail travel is more widespread in China and India. Aviation accounts for 40% of long-distance travel in OECD countries, and nearly a quarter of non-urban travel at the global level. As incomes continue to rise, passenger air transport is expected to grow substantially to 2050.

On average, the energy and emissions intensities of passenger transport by car and air are far higher than by small road modes (e.g. 2- and 3-wheelers) and public transport (bus and rail). The global well-to-wheel (WTW)[11] GHG emissions intensity[12] of cars typically ranges from about 115 grammes of CO_2-equivalent per passenger-kilometre (gCO_2-eq/pkm) to 180 gCO_2-eq/pkm, and for aviation the average is around 170 gCO_2-eq/pkm. The average emissions intensity of 2- and 3-wheelers is about

11 GHG emissions that take place during the production of transport fuels can be separated into: (1) those occurring between extraction of primary feedstocks and delivery to the final site of distribution to the end user (well-to-tank), and (2) those occurring during the combustion of the fuels in the powertrain of vehicles (tank-to-wheel). Together, these make up total WTW GHG emissions.

12 Emissions intensity varies widely, from about 60 to more than 250 gCO_2-eq/pkm, depending on the size and efficiency of the car and the number of passengers.

half that of small cars, at 58 gCO_2-eq/pkm, and the average emissions intensity of rail and public bus is less than half that of 2- and 3-wheelers.[13]

The continued dependence of road transport on oil products, together with the high energy intensity of road vehicles and airplanes, implies that energy use and emissions from passenger transport are currently determined primarily by the magnitude of road vehicle and aviation activity. Regional differences are also affected by mileages and vehicle characteristics. Despite the fact that motorised passenger activity in 2015 in China was almost 50% higher than in the United States, the aggregate energy demand and emissions due to passenger transport in China are just over half (51%) those of the United States. The discrepancy is a consequence of several factors: i) a larger contribution from aviation in the United States; ii) greater relevance of buses and rail services (more than two-thirds of total passenger activity in China and about 5% in the United States); iii) the importance of motorised 2-wheelers for personal mobility in China (nearly half of which are electric), combined with a very limited relevance of 2-wheelers in the United States; iv) usage-related elements, including, higher mileages and lower average occupancy; and v) the larger size of cars used in the United States.

Freight transport. The amount of energy used and GHGs emitted per tonne-kilometre (tkm) vary considerably in different freight modes. On a tonne-kilometre basis, light commercial vehicles (LCVs) emit about 3.5 times as much as medium freight trucks (MFTs) and nearly eight times as much as large trucks. Rail and shipping are both more than ten times more efficient per tonne-kilometre than the average heavy freight truck (HFT).

Freight currently accounts for about 40% of total transport energy use and 42% of WTW emissions. Despite accounting for only 1% of total tonne-kilometres, urban freight modes are responsible for about 21% of freight energy use and emissions. Marine shipping accounts for the majority of freight transport activity (81%), but just under one-quarter of freight transport energy use. Rail accounts for a greater share of non-urban freight in certain regions, for instance in countries where the main trade partners are not connected by sea (e.g. Russia), where large areas are landlocked (e.g. China, India, Russia and the United States), and where large volumes of commodities are transported to the coast (e.g. coal distribution by rail, as in China, India and South Africa).

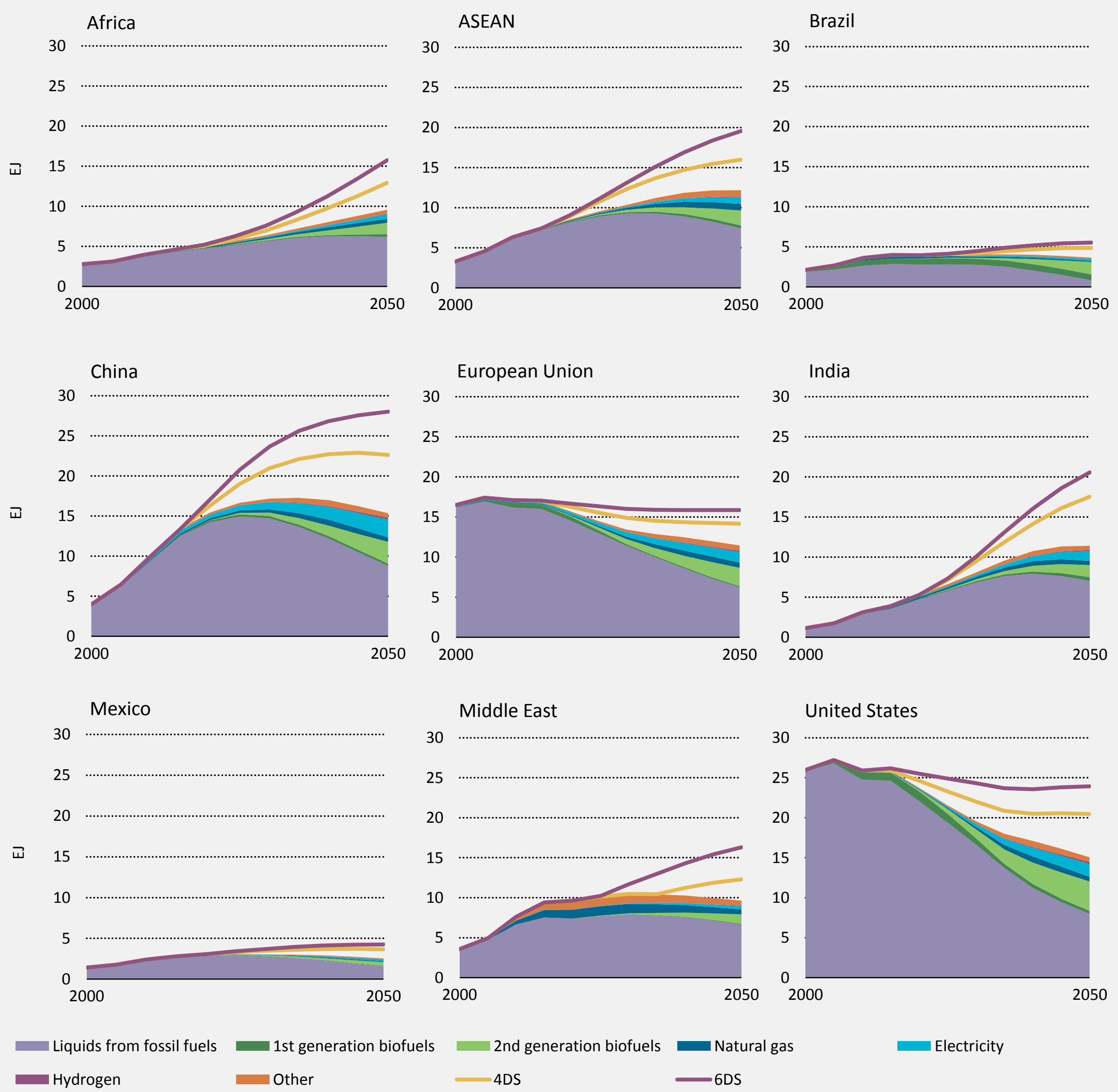
Scenario results

Meeting the 2DS requires absolute reductions in the volumes of conventional transport fuels consumed, starting within the coming decade in all OECD countries (Figure 1.12). Biofuels must gradually replace fossil liquid fuels, most rapidly in trucking and aviation. Electricity must be phased in rapidly to fuel passenger light-duty vehicles (LDVs), including cars as well as 2- and 3-wheelers, and short-distance light freight. EVs (including 2-wheelers) are expected to penetrate most rapidly in OECD countries, China and India.

Growing incomes and population, together with continued urbanisation, will drive growth in transport final energy demand across most non-OECD economies, even in the 2DS (notable exceptions are Russia and China, where energy use peaks within the coming decades in the 2DS). In the 2DS, energy consumption is expected to stabilise in Latin American and ASEAN countries and in India in the 2030s, but will continue to increase in Africa through mid-century.

13 See Figure 5.5 in Chapter 5 for the range of emissions intensities of all passenger and freight transport modes.

Figure 1.12 Final energy demand in the 2DS in major world regions by energy carrier



Key point *To achieve the 2DS, transport energy will need to start to decline in the OECD over the coming decade. Ambitious policies and technology deployments are also necessary to check demand growth across non-OECD economies.*

In non-urban transport, cars, trucks, aviation and shipping are the main energy-consuming modes. Reducing energy use and emissions from intercity passenger travel is possible through strict pricing and regulatory policies, which can spur efficiency improvements, reduce aggregate car travel, and shift activity to public modes such as intercity bus and rail. The strong policies recommended in the "key actions" below are needed to set the course towards realising the emissions abatement required in the 2DS for the transport sector. A more detailed discussion of policy measures and technological improvements needed to bring urban transport emissions in line with the 2DS targets is available in Chapter 5.

Demand for passenger aviation is expected to grow markedly over coming decades, especially as GDP increases in non-OECD economies. Reducing aviation energy use requires continuous deployment of energy-efficient technologies together with rapid expansion of high-speed rail (HSR) to provide an alternative to intra-continental air travel. Energy efficiency and operational improvements are the main technological means allowing the aviation industry to move towards the emissions reduction targets that it announced for 2020 and 2050 (ATAG, 2015a). The electrification of ground level operations and drop-in biofuels are likely to be the most viable additional instruments allowing the aviation industry to comply with these announcements (Box 1.3). The industry has also announced its intention to explore offsets as a potentially more viable means, using the market to reduce emissions, including for the 2020 target (ATAG, 2015b).

Aggressive vehicle efficiency gains in road freight – driven by fuel economy standards and higher fuel prices – could curb increases in global final energy use by long-distance trucking, which is expected to grow from 19 EJ in 2015 to 24 EJ (in the 2DS), 30 EJ (in the 4DS) or 33 EJ (in the 6DS) by 2050. Low-carbon biofuels need to provide additional contributions to achieve emissions reduction consistent with the 2DS (Box 1.2).

Low-carbon fuel shares are higher in the 2DS than in the 4DS or 6DS (Figure 1.13). Low-carbon fuels are best suited as conventional fuel alternatives for specific vehicle types, according to their energy density, supply pathway, and the usage cycle and requirements of the specific modes.

Electricity and biofuels both play key roles as substitutes to petroleum in the 2DS, but do not become a substantial part of the fuel mix in either the 4DS or the 6DS. As low-carbon energy carriers with high energy density, biofuels (Box 1.2) are uniquely suited among low-carbon alternatives for long-distance trucking and aviation. Energy densities of batteries, compressed methane and hydrogen are all far too low, and their storage costs too high, to be viable alternative low-carbon fuels in passenger aircraft, which have limited fuel storage volumes. The same issues plague heavy-freight trucking and shipping, where long ranges require large volumes of on-board energy storage, compromising cargo capacity.[14]

Box 1.2 Low-carbon biofuels: An essential piece of the climate puzzle

Biofuels can be obtained from the conversion of sugars, starches, vegetable oils, lignocellulosic materials, and other organic feedstocks into liquid and gaseous fuels. Conventional biofuel production pathways are based on fermentation, distillation and dehydration of sugars and starches. They typically rely upon dedicated cultivation of crops, such as sugar cane (e.g. in Brazil) and maize (e.g. in the United States). Sugar upgrading and advanced fermentation technologies can be used to convert intermediate compounds into hydrocarbons, including compounds suitable for use in aviation. Vegetable oils are the primary feedstock of biodiesel production pathways. In conventional pathways, vegetable oils are derived either from dedicated crops, such as palm (especially in Southeast Asia), rapeseed (in temperate climates) and soybean (e.g. in Brazil), or from waste streams (e.g. used vegetable oils). Oils are typically converted to biodiesel through transesterification processes.

Advanced conversion technologies such as hydro-processing or hydro-treating can produce a wider spectrum of hydrocarbons from vegetable and waste oils. Alternatively, lignocellulosic feedstocks (e.g. dedicated tree plantations, waste wood, switchgrass and miscanthus) can be used

14 Increasing the reliance of long-haul road freight delivery services on low-carbon electricity would require the deployment of electricity supply infrastructure along the main axes of the road network and the parallel deployment of vehicle technologies allowing its use. This solution was discussed in *ETP 2014* (IEA, 2014) but was not considered in the development of the 2DS scenario for *ETP 2016*.

to produce ethanol, biodiesel and bio jet kerosene via various biochemical and thermochemical conversion processes.

Performance varies widely within and among different feedstocks and conversion technologies in terms of GHG emissions, costs, logistics and other natural resource and environmental impacts. Performance can differ significantly even for a single feedstock and conversion pathway, due to a wide range of possible climatic, agronomic, geographic, technological and economic contexts. Consequently, different penetrations of biofuel production technologies can lead to widely disparate energy demand and GHG emissions impacts (van der Voet, Lifset and Luo, 2010; Whitaker et al., 2010), as well as variable environmental, cost and efficiency performance (JRC, 2014; ANL, 2015).

The complexity of estimating economic, environmental and natural resource impacts of biofuels production is highlighted by its contribution to land-use change (LUC), either directly through changes in the use or management of the land cultivated for biofuel feedstocks, or indirectly (i.e. as a consequence of market impacts) (Searchinger et al., 2008; Rajagopal and Plevin, 2013; Plevin, Delucci and Creutzig, 2014). LUC alters the stock of carbon sequestered in, and nitrous oxide emitted from, the soil and plants, and these changes can alter the WTW GHG emissions balance of biofuels substantially (Reay et al., 2012; Smith et al., 2012; Davidson and Kanter, 2014).

Biofuel production pathways using lignocellulosic feedstocks tend to incur low WTW emissions, especially if they rely on waste and residues (Malins et al., 2014). This can be the case even in cases where the WTW energy conversion efficiencies are very low. Ethanol from sugar cane also qualifies among the better performing options, provided that its production leads to limited LUC (this, however, depends on location- and market-specific circumstances). For these reasons, lignocellulosic biofuels and sugar cane ethanol production are expanded in the 2DS.

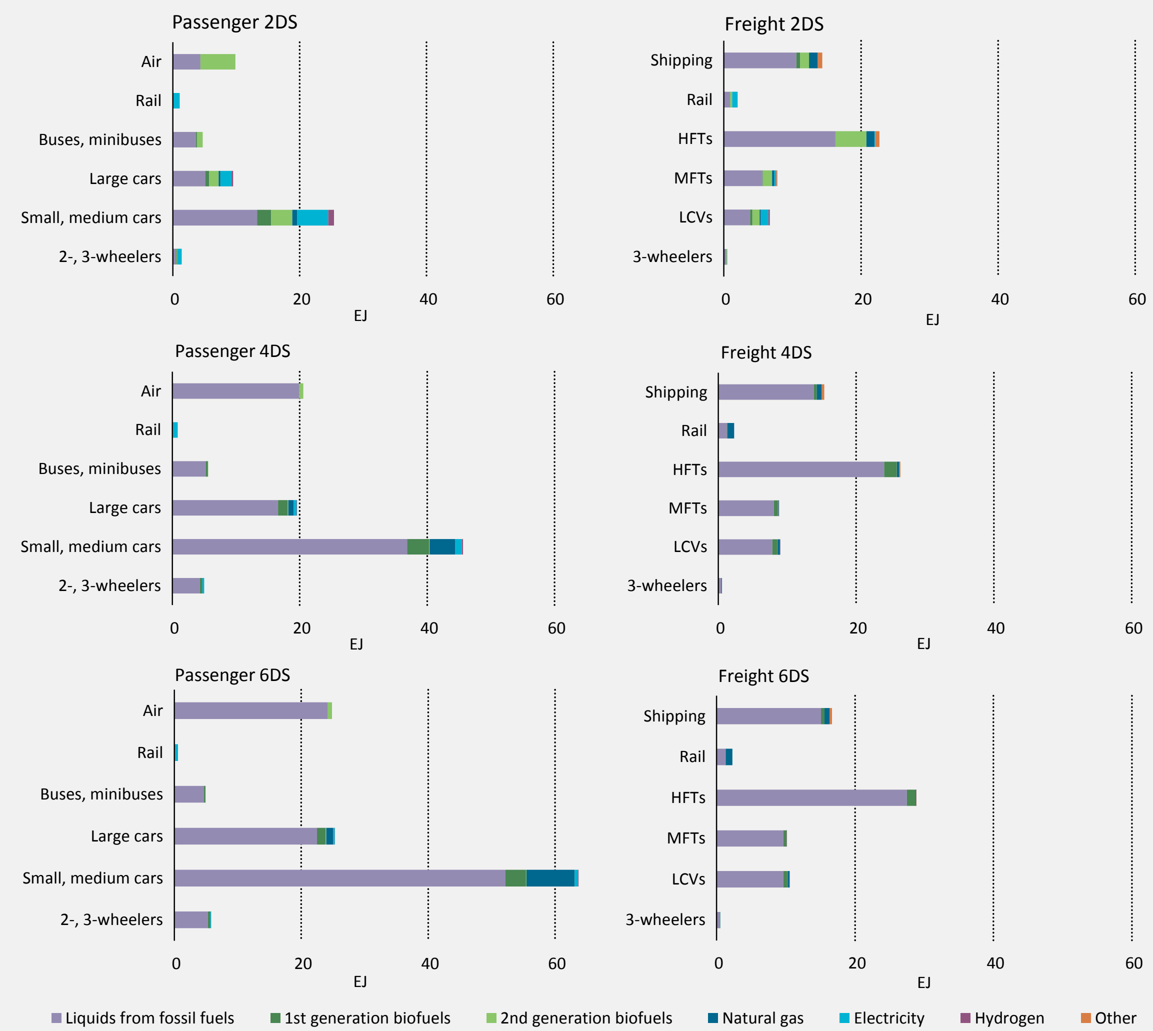
Lignocellulosic production is now at a pivotal developmental stage, with prospects for expansion hingeing upon the technical and financial performance of pioneering plants (IEA, 2015g). Biofuels development in the 2DS requires increased policy support in the form of mandates for advanced biofuels or fuel quality standards that favour pathways with the greatest reductions in WTW emissions.

Recent analysis of break-even oil prices for lignocellulosic biofuels indicates that they are currently not competitive with petroleum-based transport fuels at 2015 crude oil prices, but would require breakeven oil prices ranging from USD 100 per barrel (bbl) to USD 130/bbl (IEA, 2015g). Investment costs for plants using gasification biomass technologies are estimated to be twice as high as commercial-scale advanced biofuel plants using hydrolysis- and fermentation-based technology (IEA, 2015g). Moreover, current production of biofuels falls short of what was projected in earlier assessments (e.g. IEA, 2011), and many recent cost estimates for advanced biofuels in 2030 are not optimistic (e.g. LowCVP, 2015).

Production costs for advanced biofuels need to fall faster over the long term, so that biofuels eventually become competitive with conventional fuels once the impacts of WTW GHG emissions are incorporated (e.g. through CO_2 pricing or low-carbon fuel standards). Cost reduction opportunities exist across the supply chain, via yield increases, conversion of low-cost residues or waste feedstocks (though volumes of these are often limited), production scale-up (though with cost penalties for transporting biomass to conversion plants), improvements in the design and operation of plants, and reductions in enzyme costs.

The above considerations underscore the magnitude of the challenge facing the advanced biofuels industry, and justify lowering of biofuel demand in the 2DS in *ETP 2016* compared with previous editions. Biofuels contribute 6.9 EJ in 2030 and more than 24 EJ by 2050 to the transport energy mix. Compared with the 4DS and 6DS, biofuels production in the 2DS is 35% to 45% higher in 2030 and more than twice as high in 2050.

Figure 1.13 Fuel shares in 2050 for passenger and freight modes by scenario



Key point *Low-carbon fuels (including conventional and advanced biofuels, electricity, hydrogen, and natural gas) account for 41% of final energy consumption in the 2DS, as opposed to only 14% in the 4DS and 13% in the 6DS.*

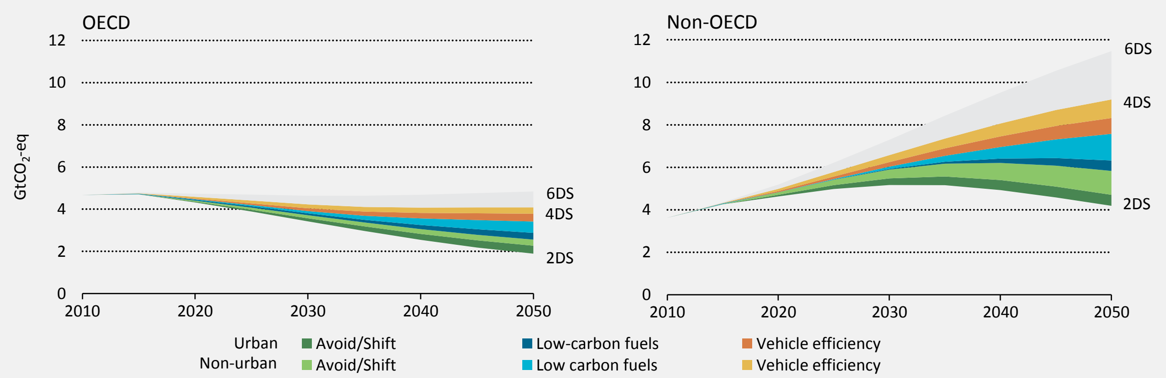
Passenger vehicle fleets need to electrify rapidly in the 2DS (see Chapter 5). In non-urban transport, passenger cars and light commercial vehicles electrify more quickly than heavy-duty road freight vehicles, driven by strong policy support. Intercity rail networks electrify rapidly as well, driven by the development of high speed rail. The deployment of fuel cell electric vehicles (FCEVs) occurs primarily in the LDV fleet, but is limited by high investment risks: hydrogen use reaches 1.5 EJ by 2050, or about 1.5% of total final energy demand.[15,16]

15 A scenario considering higher penetration of hydrogen in the fuel mix, following policy developments particularly favourable for hydrogen technologies, is discussed extensively in IEA (2015i).

16 Note that the share of electric and fuel cell electric vehicles in passenger and freight fleets is higher than their share of final energy because these technologies have higher powertrain efficiencies than internal combustion engines (see Figure 5.11 for technology penetrations in the 2-wheelers, LDV, and truck fleets in the 2DS, 4DS, and 6DS).

GHG emissions in transport follow different trajectories across global regions in all scenarios (Figure 1.14). In OECD countries, transport emissions have effectively stabilised; even in the 6DS, WTW emissions increase by less than 3%, and in the 4DS, modest policies lead to a reduction in 2050 emissions of more than 13% relative to current levels.

Figure 1.14 **OECD and non-OECD WTW GHG emissions from the 6DS to the 2DS**



Key point *Transport emissions have stabilised in OECD countries, and can be reduced to less than half the current level by 2050 in the 2DS. Across non-OECD economies, transport emissions may double or even nearly triple in the absence of strong policies, but 2050 emissions could be reduced to current levels.*

In the OECD, about a third of emissions reduction in the 2DS compared with both the 4DS and the 6DS comes from *avoiding* travel by reducing the number and length of trips or *shifting* travel to low-emission modes. The mitigation potential in the OECD is greater in urban regions for Avoid/Shift measures, reflecting greater flexibility in modal choices offered by urban environments. Another third of GHG abatement comes from *vehicle efficiency* gains, primarily in cars, trucks and airplanes, for which the potential is roughly equivalent in urban and non-urban regions. The remaining third is achieved through *low-carbon fuels*. Here potential is greater in non-urban (intercity and long-distance) transport, as drop-in jet fuels (aviation) and low-carbon biodiesels (trucking) replace petroleum-based fuels. Compressed and liquefied natural gas can replace diesel in road freight applications in certain markets, provided that certain issues (e.g. "methane slip") are addressed. The net effect in the OECD is a 22% reduction in cumulative emissions from 2010 to 2050, and a 54% reduction in 2050 emissions, relative to 4DS. Relative to the 6DS, cumulative emissions in the 2DS are reduced by 28% (59 $GtCO_2$-eq) from 2010 to 2050, and 2050 emissions are 61% lower.

Transport GHG emissions in non-OECD economies are on track to surpass those of the OECD in the next five years. By 2050, non-OECD economies' share of total transport emissions increases to around 70% in all scenarios. In the 6DS, non-OECD emissions increase by a factor of 2.6 from 2015 to 2050, reaching 11.5 $GtCO_2$-eq. In the 4DS, emissions more than double, reaching 9.2 $GtCO_2$eq. The mitigation potential of Avoid/Shift measures is greater in non-OECD economies than in OECD countries, as a consequence of the greater potential in cities that have yet to be built and hence to plan urban forms that integrate and enable public and non-motorised transport, and that can better exploit the possibility to dampen demand for personal cars that have yet to be purchased through pricing policies (i.e. "sticks") and through provision of high-quality alternatives ("carrots").

In non-OECD economies, non-urban modal shifts in passenger transport will be needed in the 2DS to shift substantial activity from aviation to HSR (e.g. as in China over the past decade). Vehicle efficiency accounts for 35% of cumulative emissions reduction in the 2DS compared with both other scenarios. Since trucks tend to be deployed earlier than cars in developing regions, heavy freight trucks make up greater shares of long-distance transport in the non-OECD compared with the OECD. Low-carbon fuels, mostly advanced biofuels for trucking and aviation, penetrate more slowly in the non-OECD due to high costs.

The aggressive emissions reduction required in aviation in non-OECD economies underscores the importance of substantial investments in HSR as an alternative to intracontinental flights in regions with growing demand for passenger aviation (Box 1.3).

Box 1.3 Reducing emissions from the fastest growing transport sector: Passenger aviation

In the OECD, aviation activity grew faster than all other non-urban modes over the past decade; by 2015 it accounted for about 40% of non-urban passenger activity (in passenger-kilometres). The global activity share is lower (23%), as intercity bus and rail make up the majority of non-urban mobility in non-OECD economies. Nevertheless, aviation demand has also grown considerably in the non-OECD (see Figure 2.30 in Chapter 2).

Technical assessments (e.g. IATA, 2013 and Vyas, Patel and Bertram, 2013) indicate that aircraft efficiency could be improved by 50% to 70% via material substitution (e.g. composites), better aerodynamics (e.g. flow control technologies, winglets and riblets, and potentially even blended wing body aircraft architectures), designs and configurations allowing higher capacity per vehicle, and more efficient engines. Powertrain technologies (e.g. geared turbofans, gas turbine components, and open rotors), electrification of ground level operations (including using electric motors for taxiing), and operational improvements (e.g. satellite navigation and systems to facilitate air traffic control) can also deliver measurable energy savings. The 2DS assumes progress in all of these areas.

Achieving the goal of the International Civil Aviation Organisation (ICAO) of realising carbon-neutral growth from 2020 (ICAO, 2013) requires ambitious deployment of energy saving technology. Without carbon offsets, meeting long-term industry targets of halving GHG emissions by 2050 from 2005 levels (ATAG, 2015a) would require even more ambitious technology deployment.

In the 2DS, both the ICAO's aspirational goal of 2% annual reductions in energy use per revenue passenger-kilometre and the target set by the aviation industry (ATAG, 2015a) to achieve 1.5% annual reductions through 2050 are surpassed. The energy intensity of the airplane fleet decreases annually by 2.6% from 2015 to 2050; cumulatively, fleet-wide energy intensity drops by 70%. These improvements match high estimates of the available technological potential, excluding innovations classified by the International Air Transport Association as future concepts and technologies (IATA, 2013).

Meeting the 2DS also requires shifting travel from aviation to a well-funded and extensive HSR network, reducing air travel via carbon pricing, and providing strong support for low-carbon fuels, which reach 55% of the total fuel demand for aviation in 2050. Aggressive policies and rapid technology improvements are needed in aviation as demand is projected to grow rapidly and alternatives are currently limited to HSR for intracontinental travel in some regions. In the 2DS, fuel pricing and provision of HSR have the potential to reduce aviation activity by 39% relative to the 6DS by 2050.

Transport investment needs

The estimates for transport investments in the *ETP* scenarios include the costs incurred in passenger and freight transport for all road modes, as well as rail, shipping and aviation. Cost estimates include vehicles and infrastructure. For instance, in the case of road modes, both vehicle and powertrain costs are calculated, as well as the costs of building new road and car parking and of maintaining existing roads and parking.

The transport investment analysis relies on a historical dataset of vehicle ownership, travel activity, and road and rail infrastructure. National and regional historic data on road and rail building inform projections of future infrastructure needs capable of accommodating projections of future vehicle activity under the 2DS and 6DS.[17]

The 6DS would require estimated total investments of USD 367 trillion between 2016 and 2050 (about 4.8% of cumulative global GDP over the same time frame). The investment requirements of the 2DS are estimated at about USD 353 trillion (4.6% of cumulative global GDP). In both cases, about 60% of the investments are for vehicles and the remaining sum is for infrastructure. The lower investment costs of the 2DS relative to the 6DS are largely a result of a significant reduction in vehicle ownership that is only partially offset by the higher costs of low-carbon vehicles and by an increase in global infrastructure costs, which goes primarily to building intercity, metro or urban rail and HSR. The significant difference in costs as compared with *ETP 2015* (IEA, 2015j) is mostly due to the revision of activity levels in the 6DS in the transport sector and partly due to the revision of methods for projecting road and rail infrastructure (Box 1.4).

Key actions

Strong, co-ordinated transport policies in all regions will be needed to reach 2DS goals. Policies must alter behaviour through pricing and regulation, spur technological development through investment and pricing signals that incorporate GHG emissions costs, drive efficiency improvements (e.g. through mode shifts and applying data technologies in logistics), and reduce aggregate activity (e.g. by increasing the cost of the most emissions-intensive modes). The following measures are critical to moving towards these goals and must be given priority over the coming decade.

At the national level, the most crucial measure is to discontinue fuel subsidies within the next decade and to adopt fuel taxes, taxing fuels according to their WTW GHG emissions (e.g. through carbon taxes). Vehicle taxation is the second fiscal policy needed to set transport emissions on a 2DS trajectory. Global vehicle purchase and circulation taxes must be ratcheted up towards levels that approach those levied in Nordic countries. For example, despite enjoying very high GDP per capita, Norway's high vehicle taxes are associated with low rates of vehicle ownership. By pegging vehicle registration taxes to environmental performance, together with other supportive policies (including exemptions from purchase tax and value added tax), Norway and the Netherlands have achieved the worlds' highest sales shares of EVs among passenger cars. Revenues from vehicle and fuel taxes can be used to subsidise purchase costs or RD&D for energy efficient technologies, or alternatively can be reinvested in public transport. The final essential national measures are regulatory: fuel economy and tailpipe emissions standards on LDVs and trucks must be broadened and tightened. Both standards must be redesigned to better reflect actual on-road conditions, to include freight trucking, and be extended to regions where they have yet to be enacted.

17 Projections of vehicle sales and stock, technology penetrations, activity, and the resultant energy use and emissions are based on GDP PPP, population and fuel price projections together with elasticity and regression-based economic and behavioural responses to policies (e.g. vehicle and fuel taxes, municipal-level transport demand management and compact cities policies). For more details on the methodologies used to project transport activity and energy use, see Annex F at www.iea.org/etp/etp2016/annexes.

Box 1.4 Revision of transport investment needs in *ETP 2016*

The cost assumptions and calculations for the transport sector in *ETP 2016* were altered from those used in *ETP 2015*. Road infrastructure build-out was revised in *ETP 2016* under the assumption that levels of congestion in developing and emerging countries would converge, as those countries became richer, towards values comparable with those that are currently observed in OECD economies. In addition, passenger rail infrastructure build-out was disaggregated into intercity, metro/urban rail, and HSR, to reflect the differences in the costs of these systems and to leverage the model developments developed for this year's urbanisation theme. The result is reduced total investment costs in the 2DS relative to the 6DS amounting to more than USD 14 trillion.

Developing and emerging countries stand to save the most: Avoid/Shift measures (including higher fuel and vehicle taxes and investments and subsidies for public transport) reduce vehicle ownership substantially in countries such as China and India. Fewer cars imply fewer roads and parking spaces, which in many non-OECD countries outweigh the additional investments in public transport (rail) infrastructure. Meanwhile, the net infrastructure costs of the 2DS, relative to the 6DS, for the European Union and the United States are positive.

Developed countries, with already saturated (or at least mature) car markets, locked-in road infrastructures and competitive profiles with respect to technology development and innovation, will need to invest more and earlier (bearing higher learning costs) to transition to "clean" vehicles (primarily hybrids and EVs, as well as FCEVs). In the OECD context, additional public rail infrastructure needs outweigh savings from reduced road building.

Fuel savings are unambiguous; the global savings on fuel under the 2DS total upwards of USD 90 trillion. They are also more evenly distributed across countries and regions, as the up-front investments in clean vehicles pay off more evenly across OECD and non-OECD countries.

One way to understand the investment costs is to consider the additional costs of alternative ("clean") vehicle technologies holding the number of vehicles constant. The relative costs of a scenario in which alternative powertrain technologies are on par with those in the 2DS (but in which the GHG reductions are not – as it lacks the policy measures and investments required to realise avoided car travel and shifts away from personal cars) are higher: about USD 6 trillion in investments would be needed globally.

Countries must start benchmarking operations to determine the efficiency of different vehicle categories in the main truck markets as the first necessary step toward setting vehicle efficiency regulations for trucks. Benchmarking must precede regulation design, as it requires software simulation, stakeholder consultation and extensive data collection.

Fuel economy and emissions standards; differentiated vehicle taxes; public charging infrastructure investments; and continuing, consistent and substantial support for RD&D are all needed to drive a rapid transition to electricity in passenger LDVs, buses and rail.

Within a supportive national policy environment, local policies can be designed to address traffic congestion, health and local environmental impacts of transport in cities (see Chapter 5). Investment in public transport and walking and cycling infrastructure is needed to ensure that people have access to affordable, attractive and comfortable alternatives to cars, particularly in light of increased prices for vehicles and fuels.

Rapid demand growth projected in passenger aviation and long-distance road freight will require investments in alternatives (high-speed passenger rail for aviation and freight rail for trucking), as well as consistent policy support for advanced biofuels, including RD&D support and policies such as mandates or low-carbon fuel standards.

Particularly in aviation, ambitious efficiency improvement targets set by the industry are unlikely to be met without correspondingly aggressive fuel or carbon taxes. A schedule of fuel taxes, linked to the WTW carbon intensity of fuels and increasing over time, will be needed to incentivise efficiency improvements.

Industry

Current status

Global industrial final energy use reached 152 EJ[18] in 2013 with corresponding direct carbon emissions of 9.0 $GtCO_2$. The 3.4% annual average growth in energy use from 2000 to 2013 continued the long-term trend of increasing industrial energy demand, with the exception of some temporary drops due to economic downturns. Industrial final energy consumption has increased since 2000 in Africa, Asia, Latin America and the Middle East, while in OECD economies overall industrial energy consumption has decreased slightly, 0.7% on average per year. The distribution of energy use across industry sectors has not changed significantly since 2000; energy consumption in energy-intensive industry[19] has grown by 49% since 2000, while non-energy intensive sectors' consumption grew by 37%. Energy-intensive industry now makes up 68% of all industrial energy use, compared with 66% in 2000.

Economic pressure on industry has increased in recent years, particularly in energy-intensive industries that face global competition. Regulations and material, energy and labour costs differ from region to region, creating competitive pressure, and a global economic slowdown over the past few years has exacerbated the situation. Demand for industrial materials has continued to grow globally, with consumption in some emerging economies picking up even as demand per capita in the developed world has stabilised. At the same time, some regions are dealing with overcapacity in key industry sectors. In 2013, for example, nominal production capacity for crude steel globally was 2 164 million tonnes (Mt) per year, while demand stood at 1 648 Mt. The 76% utilisation rate was one of the lowest in history (OECD, 2015). The cement sector, similarly, has seen several years of excess capacity and consolidation; some sources put the capacity utilisation rate of cement plants in China at less than 50% and around 55% in India (Global Cement, 2015). Such excess capacity can work both for and against efficiency in industry: because it endangers the competitiveness and profitability of the sector, it makes investment in retrofits, upgrades and other energy efficiency projects more difficult. However, it can also provide the opportunity to retire the less efficient stock, improving the sector-wide average performance level.

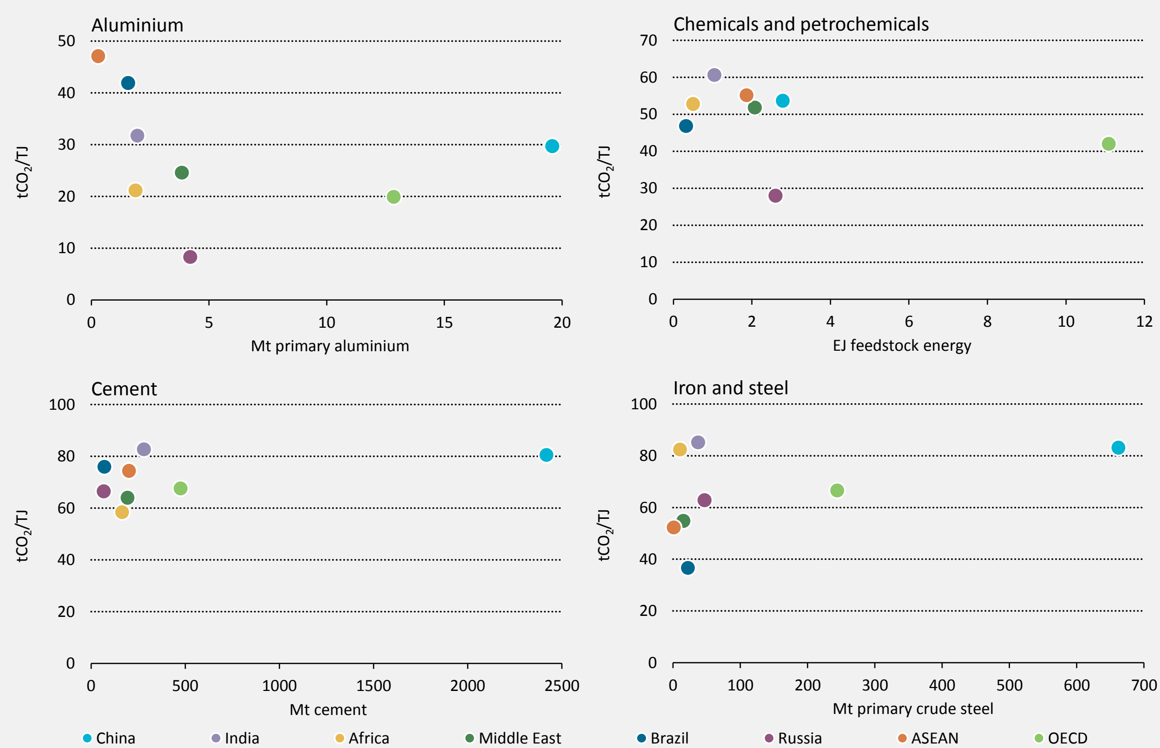
The difficult economic circumstances underline the need for prioritisation in developing sustainability strategies for industry, based on a clear and detailed view of current industrial energy use and CO_2 emissions. Industrial energy efficiency and CO_2 emissions intensity – and thus the most cost-effective transition to a reduced carbon footprint in 2050 in the 2DS – can vary significantly across regions and sectors. To remain on the 2DS pathway, it is important to track the progress of each sector by region to target efforts towards the area where the most impact can be made.

18 Unless otherwise stated, final industrial energy demand includes energy embedded in petrochemical feedstock and energy use in blast furnaces and coke ovens.

19 In IEA modelling, five energy-intensive sectors are considered: chemicals and petrochemicals, cement, iron and steel, aluminium, and pulp and paper.

To assess where industrial CO_2 savings potential exists, both energy-related CO_2 intensity relative to best practice levels, and absolute production volumes in the sector should be considered (Figure 1.15). The energy-related CO_2 emissions intensity can be improved by implementing technological changes, such as best available technologies (BATs), but can also be influenced through structural changes to a sector, by facilitating wider deployment of less carbon-intensive secondary process routes, such as scrap-based electric arc furnaces (EAFs). In some sectors and regions, one option may be less costly than the other, and in others, both options may be needed to fully exploit emissions reduction opportunities.

Figure 1.15 **Direct industrial energy-related CO_2 emissions intensity and selected material production by region and sector, 2013**



Notes: tCO_2/TJ = tonnes of CO_2 per terajoule. Direct CO_2 intensities are based on direct energy use (feedstock energy use is excluded) and energy-related CO_2 emissions (process emissions are excluded) in each sector. In the chemicals and petrochemicals sector, feedstock energy use has been represented in the above graph as a proxy for production levels. The global average process emissions for the cement sector in 2013 are 0.54 tCO_2 per tonne (t) clinker; in iron and steel, 0.13 tCO_2/t blast furnace-based crude steel; in aluminium, 0.81 tCO_2/t aluminium; and in chemicals and petrochemicals, 17.7 tCO_2/TJ petrochemical feedstock.
Sources: IEA estimates; FAO (2015), data from *Forestry statistics*; USGS (2015), *Minerals Yearbook Volume I – Metals and Minerals*; Worldsteel (2015), *Steel Statistical Yearbook 2015*.

Key point *Policy makers should prioritise their efforts co-operatively with industry where they will have the greatest impact in reducing CO_2 emissions.*

Countries must simultaneously tackle the challenge of process emissions[20] as, in some cases, it is critical to go beyond the current technical limit of energy efficiency improvements to further reduce carbon emissions to reach 2DS levels. For example, the

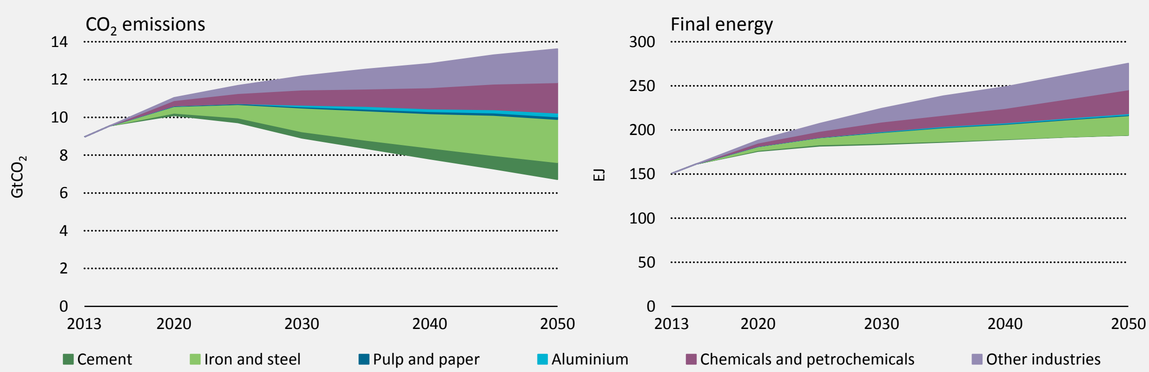
20 Process emissions refer to the share of CO_2 emissions that are inherently generated in the reactions taking place in an industrial process, such as the CO_2 released during calcination of limestone in cement kilns. Process emissions represent 64% of overall cement direct emissions, 6% in iron and steel, 39% in aluminium and 41% in chemicals and petrochemicals.

energy-related CO_2 emissions intensities shown in Figure 1.15 for the cement sector are less dispersed regionally than in other sectors, indicating more homogeneous energy performance (more likely closer to best practice), fuel mixes, and technologies. In other sectors, such as iron and steel and aluminium, greater variation in rates of secondary production[21] and in energy efficiency levels explains the greater variation in energy-related direct CO_2 intensity levels. The cement sector's high level of process emissions – 64% of the total sector CO_2 emissions in 2013 – combined with the homogeneity of the sector means that solutions for the cement sector will need to go beyond energy efficiency improvements and switching to low-carbon fuels to reach the 2DS.

Scenario results

As demand for primary industrial materials continues to grow, and in the context of a competitive global industrial marketplace with shifting regional centres of production, there is a strong need to support a low-carbon transition in industry globally. In China, the production of key materials slows in the medium term; production of crude steel falls by 372 Mt (45% of 2013 production) from 2013 to 2050. This is offset by strong demand growth in India and the ASEAN region, which collectively see a more than fivefold increase in crude steel production, growing by 571 Mt by 2050. In the cement sector, China's production decreases by 52% to 1 149 Mt in 2050, while India and ASEAN increase production by 180% to reach 1 348 Mt. Despite regional differences in industrial energy demand growth, rising material production leads to unsustainable increases in global emissions in the 4DS and the 6DS (Figure 1.16).[22]

Figure 1.16 **Direct industrial CO_2 emissions and final energy reductions in the 2DS compared with the 6DS**



Key point *The 2DS requires significant reductions in industry's energy footprint and decoupling of direct CO_2 emissions from energy consumption in the sector.*

Approaching a 2DS CO_2 emissions trajectory requires industrial energy consumption to be decoupled from the increasing demand for materials. Overall, industrial final energy consumption in 2050 is 26% lower in the 2DS than in the 6DS, with average annual growth of 0.9%, compared with 2.2% in the 6DS. The production of crude steel consumes 29 EJ of final energy in 2050 in the 2DS, 43% less than the 51 EJ in the 6DS for the same activity

21 Secondary production refers to production of a material from scrap or recovered material.
22 Greater recycling of materials such as steel, aluminium, paper and plastics is embedded in the 2DS, resulting in a greater penetration of recycled or scrap-based production routes, which are typically less energy intensive. The overall demand for these materials, however, remains the same across the different scenarios.

level. Other energy-intensive sectors also contribute: chemicals and petrochemicals use 25% less energy in 2050 in the 2DS than in 6DS, and pulp and paper uses 13% less, aluminium 12% less, and cement 2% less. Non-energy intensive industry's average annual energy consumption growth is limited to 0.2% in the 2DS, reaching 58 EJ by 2050, compared with 88 EJ in the 6DS.

To remain on the 2DS pathway, overall direct industrial CO_2 emissions need to be 49% below 6DS levels globally in 2050, at 6.7 $GtCO_2$ (Figure 1.16). In 2050, 33% of this emissions reduction (2.3 $GtCO_2$) comes from the iron and steel sector, 23% from chemicals and petrochemicals (1.6 $GtCO_2$), 13% from cement (0.9 $GtCO_2$), 3% from aluminium (0.2 $GtCO_2$), 2% from pulp and paper (0.1 $GtCO_2$), and the remaining 26% from non-energy intensive industries (1.8 $GtCO_2$). India contributes 26% of 2050 emissions reductions; China contributes 24%, OECD countries 18%, Africa and the Middle East 14%, and the rest of the world 18%.

While global industrial energy use continues to rise slightly through to 2050 in the 2DS, direct CO_2 emissions peak by 2020. Decreases in direct CO_2 intensity per unit of energy in all industry sectors make this possible, mainly driven by a shift towards lower-carbon fuels and feedstocks, increased recovery of excess energy, and deployment of innovative low-carbon process technologies in the long-term, including CCS.

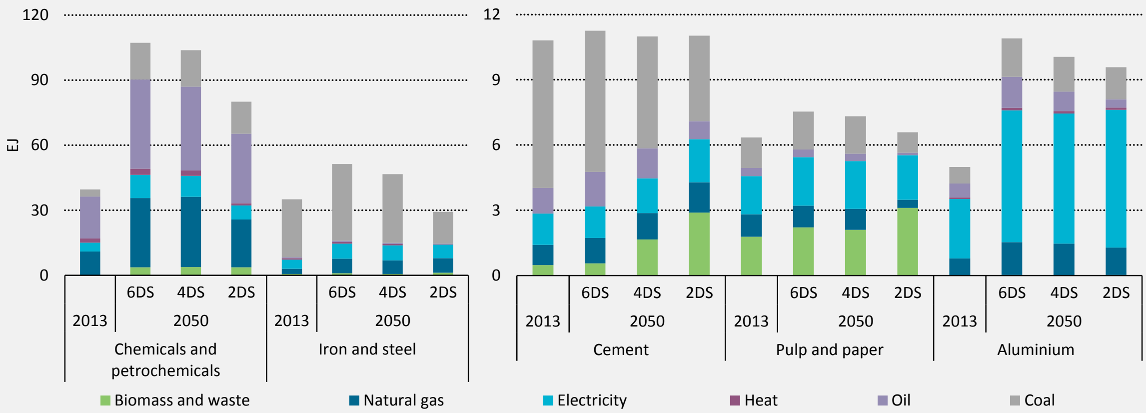
In the short term, emissions reduction is mainly achieved through energy efficiency, which accounts for 86% of direct CO_2 emissions reduction in 2020; in the longer term, as the industry sector's energy footprint approaches best performing levels, industrial energy users need to implement additional measures to reduce emissions, and the share from energy efficiency falls to 55% by 2050. In 2050, energy efficiency accounts for emissions reductions of 3.8 $GtCO_2$ compared with the 6DS; at the same time, growth in energy use slows significantly, and consumption in 2050 is 73 EJ lower than in the 6DS. Energy efficiency incorporates a diverse range of measures. In the cement sector, clinker substitution allows producers to create more cement per tonne of energy-intensive clinker. In the pulp and paper sector, co-generation based on byproducts from the production process allows plants to generate more heat and electricity without increasing the level of fuel combustion.

Innovative processes[23] make up 1.7 $GtCO_2$ of emissions reduction in 2050, one-quarter of the industrial total. These include upgraded steelmaking processes based on smelt reduction or direct reduced iron, inert anode technology in the aluminium sector, and biomass-based process routes for chemicals production, as well as CCS applications such as partial oxycombustion with carbon capture in cement kilns. Many of the innovative process technologies require integration of carbon capture into the process and facilitate the separation of CO_2 by producing concentrated CO_2 streams as inherent by-products.

Switching to lower-carbon fuel and feedstock mixes contributes 1.2 $GtCO_2$, or 17% of 2050 emissions reduction. Biomass increases from 2% to 11% of overall energy consumption in the cement sector by 2050 and from 28% to 47% in the pulp and paper sector (Figure 1.17). Electrification of industrial processes also plays an important role in the 2DS; the iron and steel sector increases its electricity consumption as a share of total consumption from 12% to 21%, by deploying innovative process routes and maximising the EAF process route, which enables both CO_2 and energy reductions. The fuel mix in chemicals and petrochemicals shifts along with changing process routes, while overall energy consumption grows quickly due to material demand pressure. The deployment of inert anodes for aluminium smelting in the 2DS decreases the need for fossil fuel feedstock for conventional anodes.

23 For the purposes of the ETP Industry model, innovative processes are defined as low-carbon process technologies that have not yet been demonstrated, but could become commercially available during the modelling time horizon.

Figure 1.17 Final industrial energy consumption by sector



Key point *By 2050 in the 2DS, biomass, waste and electricity grow to 25% of final energy consumption in energy-intensive industry, while overall energy use decreases to 24% less than in the 6DS.*

In 2050, recycling accounts for the remaining 240 million tonnes of CO_2 ($MtCO_2$) of emissions reductions. Recycling plays a role primarily in iron and steel, where it makes up 51% of production, and in aluminium (34%).[24] Increased plastics recycling rates also help to alleviate the growing demand for primary chemicals in the 2DS, and the production of recovered paper as a share of total paper and paperboard production increases slightly, despite an already high 54% share in 2013. The impact of recycling on emissions reductions depends on the amount of available scrap materials. While it offers significant energy and CO_2 benefits compared with primary production, these should be weighed against the impact of material efficiency strategies that could reduce the amount of scrap available, limiting the uptake of secondary routes.

Though the 6DS-2DS comparison captures the full picture of necessary emissions reductions, the 4DS also provides some additional insight into recent international commitments to address climate change, and newly announced policies and pledges at the national and regional levels. The 4DS assumes that these pledges are met, and that additional RDD&D spending is effective in bringing innovative technologies to market. Although not as ambitious as the 2DS, the 4DS requires significant policy and technology shifts. In the industry sector, the 4DS leads to 256 EJ of final energy consumption in 2050, which is a 7% reduction from the 6DS, but still 24% more than in the 2DS (Figure 1.17). As an important part of the CO_2 reductions, the 4DS considers deployment of CCS beginning in 2020, and scaling up to capture 506 $MtCO_2$ in 2050, compared to 1.7 $GtCO_2$ captured in the 2DS, and none captured in the 6DS. The 4DS also includes implementation of energy efficiency measures, switching to lower carbon fuels, BAT deployment, and commercialisation of innovative low-carbon processes, though sectors transition at a slower pace than in the 2DS.

24 In the aluminium sector, this refers to the share of new and old scrap-based aluminium in total liquid aluminium. Internal scrap is excluded for consistency with industry statistics.

Industry investment needs

Globally, in the 6DS, estimates of total cumulative investment in energy-intensive industry ranges from USD 9.5 trillion to USD 10.5 trillion, and for the 2DS, from USD 10.9 trillion to USD 12.4 trillion. Between USD 1.4 trillion and USD 2.0 trillion additional cumulative investments are estimated to be required in the 2DS in the five energy-intensive industry sectors. These estimates are based on bottom-up modelling of the five sectors, including capital costs for industrial process equipment installed during the model horizon. Fuel costs and fixed operating and maintenance costs are excluded from these estimates, as are costs associated with purchased heat and electricity. Financial costs are also excluded from our analysis, and cost estimates are undiscounted.

Regionally, China accounts for 32% of the global cumulative additional investment in the 2DS compared to the 6DS. OECD economies account for 31%, India for 12% and other non-OECD economies for 25%. In terms of cumulative total investments in the 2DS, however, 29% of the global total investment occurs in China, 20% in OECD economies and 12% in India, with investment in other non-OECD economies making up the remaining 39%. The OECD economies play a larger role in terms of additional investment than in total investment, while the non-OECD economies have a larger share of total investments than additional. This effect is primarily due to a "leapfrog" effect; regions with higher industrial activity growth rates and lower levels of technology lock-in can build up capacity using advanced technology rather than replacing existing capacity with newer stock, which minimises the amount of additional investment needed in the 2DS compared with the 6DS.

Box 1.5 Changes from *ETP 2015*

The *ETP 2016* industry scenario results are based on the *ETP* industry model, which has been reviewed and revised since the previous results in 2015. During each modelling cycle, the base year is updated to reflect the most recent IEA Energy Balance. Prior to *ETP 2016*, additional changes that affect the outcome of the analysis include:

- Conversion of the aluminium sector model to a TIMES–based,[24] linear optimisation framework including additional technology detail.
- Revised base-year energy consumption data for China based on revisions to the official Chinese energy statistics, including some step changes, particularly in coal consumption in blast furnaces and coke ovens in the iron and steel sector.
- Updates to overall sectoral activity projections for industry, with more detailed revisions in energy-intensive sectors. Some significant revisions include:
  - advancement of the peak in cement production in China to 2015 from 2020
  - significant increases in crude steel demand in India and a steeper decline in crude steel demand in China
  - a shift of aluminium production from Latin America to other regions such as Africa and China
  - moderated pulp production projections in all regions, and flattened demand for paper and paperboard in China
  - increased production of benzene, toluene and xylene (BTX) in Africa, Latin America and emerging European economies, shifting away from the Middle East and China
  - a shift in the regional shares of ethylene production towards North America
  - revisions to exogenous assumptions and drivers in some energy-intensive sectors where new data were available, particularly for energy intensity values of particular process routes or technologies.

25 TIMES = The Integrated MARKAL-EFOM System (Annex A).

Key actions

Staying on track to meet the 2DS in the industry sector will require significant action not only from industrial energy users in the private sector, but also from governments and society. All stakeholders should be engaged in creating a strategy that enables reductions in CO_2 emissions without compromising competitiveness or economic growth, and takes into account both the challenges facing industry and the opportunities of a low-carbon transition. This strategy should consider the entire energy system, and take an integrated approach to optimise energy use and reduce carbon emissions where it is most efficient and least costly to do so.

Industry should work with policy makers to ensure that strategies are realistic and achievable, but still sufficiently ambitious to meet the 2DS. Collaborating and sharing knowledge among companies and across sectors and regions will accelerate learning both in terms of technology development and best practices. Implementation of BATs and energy management systems should be a priority for industrial users, with the support of policy makers through measures such as equipment energy performance standards, including performance-tracking mechanisms. Similarly, co-operative frameworks including both private- and public-sector stakeholders are critical to achieving 2DS goals; they should prioritise action on low-carbon industrial development and encourage information exchange on best practices and innovation progress. Private-sector industry stakeholders also need to pursue RDD&D of innovative low-carbon technologies that could unlock dramatic reductions in energy use and emissions.

Without supportive, stable and long-term policy frameworks, industry will be unable to reach its full potential of contributions to the 2DS. Broader energy and climate policy strategies also have an impact on industry. Setting economy-wide, legally-binding targets for CO_2 emissions reduction and energy efficiency would clear the way for more specific, industry-focused policies. Phasing out fossil fuel subsidies – or implementing a carbon pricing mechanism – to provide a clear price signal that incorporates the negative externalities of emitting CO_2 would create incentives for lower-carbon industrial production. In doing so, policy makers must both acknowledge and take steps to counteract the risk of adverse effects from an internationally asymmetric carbon pricing system or regulatory framework, both locally and through international co-ordination. The 2DS requires that policy makers also take ownership of this transition and enact policies to facilitate the necessary investment to reduce industrial energy consumption and CO_2 emissions.

Policy actions should include incentives for energy efficiency in industry and adoption of BATs, such as fiscal mechanisms tailored either to particular industry sectors or to cross-cutting technologies, which will see results in the short term; efficient industrial equipment standard-setting; and technology transfer schemes. They should also include actions to support RDD&D in the near term, though the impact will be seen in the longer term, such as results-oriented risk-mitigating mechanisms to provide public funding and leveraging those funds to unlock additional private funding for RDD&D programmes.

Streamlining grid access regulations and developing a nationally and regionally integrated heat and cooling infrastructure planning strategy could facilitate better integration of industrial facilities, and increased utilisation of industrial excess heat, lessening industrial energy demand and the overall CO_2 impact of the energy system. The development of CO_2 transport and storage infrastructure for the power sector could improve the economic viability of CCS projects in industry. Similarly, regulations to promote material resource efficiency (e.g. metal, paper and plastic recycling; co-processing of waste in cement kilns; using blast furnace slag as a clinker substitute; and reducing the generation of industrial waste products on-site) would also have an impact on industrial energy use and emissions. Impacts beyond the boundaries of industry should also be considered; for example, development of new high-strength or lightweight materials, extension of material lifetimes, or material substitution in manufacturing could improve the environmental impact of final products during their use or enable energy and emissions benefits in other end-use sectors, as well as influencing future demand for industrial materials. These strategies require policy makers to look at energy use and emissions from a systemic perspective and co-operate with stakeholders to explore synergies along product value chains.

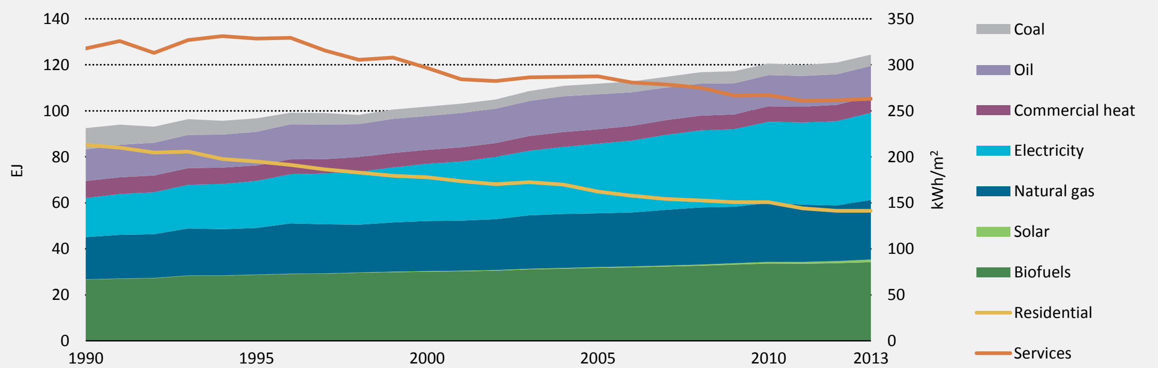
Delaying action would make the 2DS more costly and more difficult to realise. Deploying innovative process technologies – such as CCS, which some industry sectors begin using as soon as 2020 in the 2DS – requires time and capital for RDD&D in order to be scaled up commercially. Progress should be monitored and verified using robust datasets. Improving the scope and technological detail of publicly available industrial energy statistics will lead to more effective policies.

Buildings

Current status

The global buildings sector, comprising the residential and services sub-sectors consumes nearly 125 EJ, or over 30% of total final energy (Figure 1.18). The residential sub-sector alone accounts for nearly three-quarters of building energy use. Buildings also account for half of global final electricity demand, with global buildings electricity consumption having more than doubled since 1990. In some regions, electricity demand in buildings increased by more than 500% between 1990 and 2013, and electricity now represents more than 30% of global energy use in buildings. When upstream power generation is taken into account, the buildings sector is responsible for slightly less than one-third of global CO_2 emissions.

Figure 1.18 Global building energy consumption and energy intensity by subsector



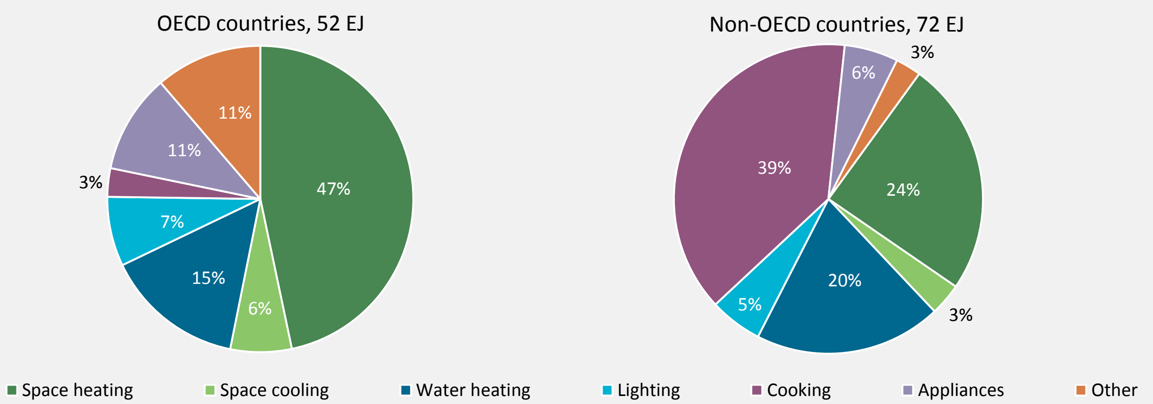
Source: Calculations derived from IEA (2015f), *World Energy Statistics and Balances 2015*, www.iea.org/statistics.

Key point *Building energy intensities have improved since 1990 but not enough to offset strong growth in total building floor area. As a result, global building energy consumption increased by 35% since 1990.*

While global energy consumption in buildings increased by more than 35% between 1990 and 2013, the overall performance of buildings (in terms of average energy demand per square metre [m^2]) has continued to improve since 1990 as the result of building policies and energy efficiency measures. The average energy intensity of residential buildings decreased by 35% from nearly 220 kilowatt hours (kWh) per m^2 in 1990 to roughly 140 kWh/m^2 in 2013. Services buildings similarly improved, by roughly 20%. However, global floor area increased by 95% in residential buildings and 75% in services buildings, so energy intensity improvements have not been enough to offset the energy consumption associated with continued growth in the size of the sector.

By 2050, global building floor area is expected to double, with 85% of anticipated growth in non-OECD countries. This will have implications for buildings sector energy demand, as energy use across OECD member and non-member countries varies considerably (Figure 1.19). Space heating accounts for slightly less than half of building final energy consumption in OECD countries, while water heating and cooking represent nearly 60% of building energy use in non-OECD countries (largely based on traditional use of biomass). Even when use of biomass is excluded, cooking and water heating still represent roughly 20% of building energy use in non-OECD countries, as space heating needs are far less important in many developing countries than in colder climates such as Europe, China, Russia, the United States and Canada. Space cooling demand is still a small portion of building energy loads in non-OECD countries, although it is growing rapidly, as many non-OECD countries are in hot or hot-humid climates.

Figure 1.19 **Building final energy consumption by end use, 2013**



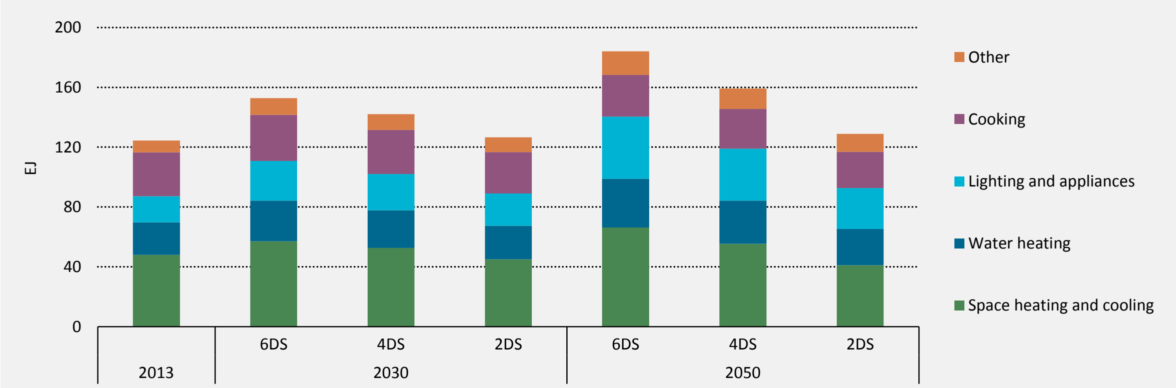
Note: "Other" refers to other building equipment (everything from refrigerated display cabinets to electric motors, information technology networks and x-ray machines) not accounted for in the six principal building end uses.
Source: Calculations derived from IEA (2015f), *World Energy Statistics and Balances 2015*, www.iea.org/statistics.

Key point *Space heating continues to dominate building energy use in OECD countries, while cooking and water heating account for nearly 60% of buildings energy consumption in non-OECD countries.*

Scenario results

If no action is taken to improve energy efficiency in the buildings sector, energy demand is expected to increase by another 50% under the 6DS (Figure 1.20). Nearly 80% of this growth occurs in non-OECD countries, as access to electricity and commercial fuels, household wealth, improved living standards and buildings sector size (i.e. floor area and total households) all continue to increase. China and India are expected to account for nearly 30% of total energy demand growth in the 6DS, while demand in most OECD countries increases only slightly or even plateaus, as consistent with recent trends. Electricity use in buildings increases by almost 140%, while biomass consumption decreases by 15%, with households shifting to modern energy sources as incomes rise and access to electricity improves.

Figure 1.20 Global building final energy consumption by end use and scenario to 2050



Key point *Building energy use is expected to increase another 50% over 2013 levels without strong action to improve energy efficiency. Energy demand in 2050 is 30% lower in the 2DS, with space heating and cooling reductions accounting for 45% of energy savings.*

Under the 4DS, global building energy consumption grows to nearly 160 EJ in 2050 (about 15% lower than the 6DS, but still roughly 30% higher than 2013) as the result of increased energy efficiency measures across end-use technologies (e.g. heating and cooling equipment, lighting and appliances) and shifts away from traditional use of biomass for water heating and cooking in non-OECD countries. Improved adoption and enforcement of building energy codes for new building construction also help to curb space heating and cooling energy demand growth, especially in non-OECD countries. However, these improvements are still not enough to offset the significant growth in building household and floor area additions to 2050. Deep energy renovations of existing buildings remain limited under the 4DS because of insufficient policy measures to address the necessary market uptake and cost-effectiveness of those measures.

In the 2DS, effective action to improve building energy efficiency could limit building final energy demand growth to just above 2013 levels (5% increase), without changing comfort levels or requiring households to reduce their purchases of appliances and other electronic equipment. Space heating and cooling demand is reduced by 40% in the 2DS compared with the 6DS, while lighting and appliances energy consumption is cut by 35%. Cooking energy demand is reduced by 15%, and water heating and other miscellaneous equipment are both reduced by 25%.

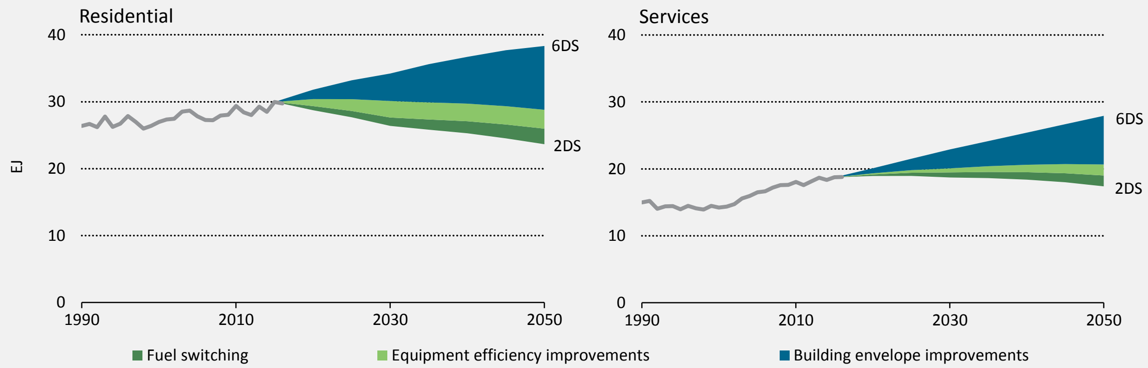
Coal and oil use in the buildings sector decreases by 75% under the 2DS compared with 2013, while natural gas consumption falls by 15%, or 40% below 6DS levels in 2050. Electricity demand under the 2DS decreases 33% in 2050 compared with the 6DS as the result of energy efficiency measures, including improvements in building envelopes (e.g. windows, doors, roofs, walls, foundations and air sealing), and despite a 250% increase in the use of heat pumps. Commercial heat (district heating) remains roughly constant, despite significant improvements in building envelopes, as additional buildings are able to join existing networks without having to increase heat production capacity. By contrast, solar thermal use, in particular for water heating, increases by 850% in the 2DS over 2013 levels. Biomass use continues to decrease as household incomes and access to electricity improve in developing countries.

Space heating and cooling are a critical priority area for energy efficiency action in the buildings sector. Space heating accounts for more than one-third of global energy use in buildings and continues to be the largest energy-consuming end use to 2050 under both the 6DS and the 2DS. Space cooling, while a significantly smaller portion of energy demand in buildings today (roughly 5%), is the fastest-growing end use in buildings and could increase by as much as tenfold in some hot, rapidly emerging economies, such as India and Mexico. Concerted effort is needed to improve building envelope efficiencies and reduce growing demand for cooling.

Through rigorous building energy policies for new construction and deep energy renovations of existing buildings, building envelope improvements could contribute to two-thirds of space heating and cooling reductions in 2050 under the 2DS, or roughly 20% of total building energy savings that year (Figure 1.21). In the services sub-sector, building envelopes represent nearly 70% of heating and cooling energy savings to 2050, partly because turnover and demolition rates of commercial and other services buildings are typically faster than for residential stock. Another 20% of cumulative energy savings to 2050 under the 2DS comes from more efficient equipment, through minimum or mandatory energy performance standards (e.g. mandatory condensing boilers) and strong uptake of high-efficiency technologies (e.g. heat pumps). The remaining 15% of savings comes from shifts away from traditional use of biomass (e.g. to solar technology and high-efficiency pellet stoves) and away from inefficient use of fossil fuels (e.g. to mandatory condensing or instantaneous gas boilers).

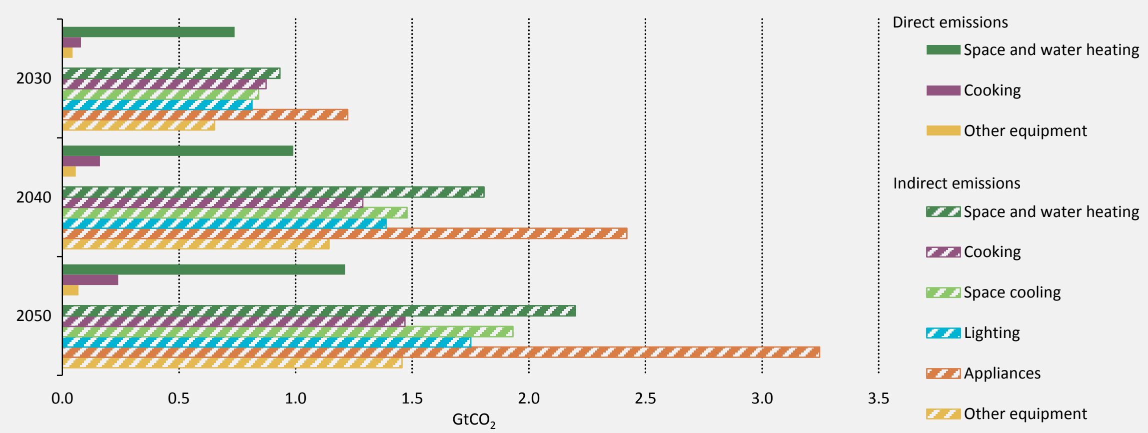
Under the 2DS, energy savings in the buildings sector could reach 55 EJ in 2050, almost equivalent to the total final energy consumption of Africa, the Middle East and non-OECD Americas in 2013. Those energy savings, paired with decarbonisation of the buildings sector and upstream power generation, would lead to an 85% reduction in building-related CO_2 emissions, or roughly 13 $GtCO_2$. Nearly 1.6 $GtCO_2$ comes from direct buildings emissions reduction through shifts away from fossil fuels in space heating, water heating, cooking and other miscellaneous equipment (Figure 1.22). The remainder comes from reductions in CO_2 emissions from electricity and commercial heat consumption, where roughly 33% of indirect emissions reduction in buildings comes from building energy efficiency improvements. Those energy efficiency improvements in buildings also help to reduce carbon emissions in the power generation sector.

Figure 1.21 Heating and cooling final energy savings, 6DS to 2DS



Key point *Envelope improvements represent two-thirds of space heating and cooling energy savings in 2050. Efficient equipment and shifts away from intensive fuels (e.g. biomass) account for another 180 EJ of cumulative energy savings to 2050.*

Figure 1.22 Buildings sector direct and indirect emissions reduction, 6DS to 2DS



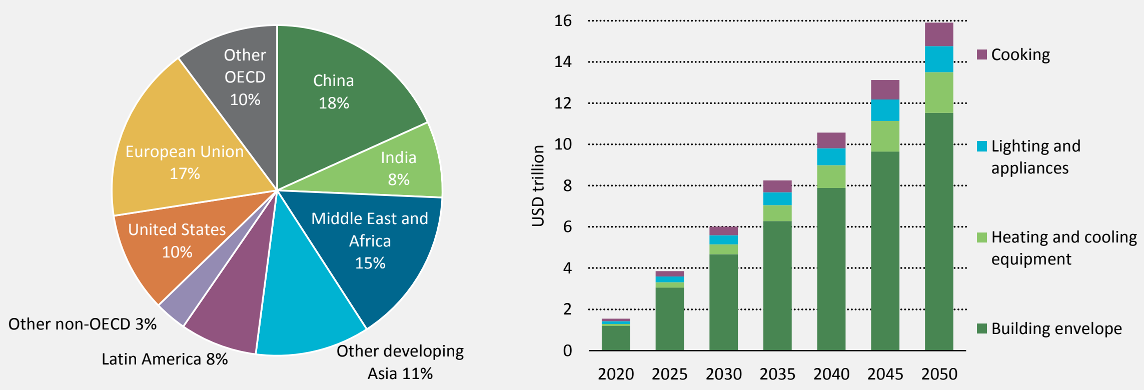
Key point *Energy efficiency and reduction of fossil fuel use, together with decarbonised electricity and commercial heat supply, can reduce buildings carbon emissions by more than 13 $GtCO_2$ in 2050.*

Buildings investment needs

Absolute cumulative investment needs in the buildings sector under the 2DS (excluding investments in building infrastructure) are roughly USD 45 trillion. Decarbonising the buildings sector in the 2DS requires cumulative additional investments of USD 16 trillion between 2016 and 2050 in comparison with the 6DS. These investments include costs for energy-consuming equipment purchases (e.g. boilers, heat pumps, clean cook stoves, solar thermal collectors and connections to district energy networks), purchases of lighting fixtures (e.g. fluorescent bulbs and light emitting diodes [LEDs]) and household appliances, and costs for building envelope energy efficiency measures.[26]

On a regional level, most (63%) of the additional investment is required in non-OECD countries, notably China (18%), India (8%), other developing Asia (11%) and Africa (11%), due to the strong growth in new building additions and expected purchases of energy-consuming equipment between 2015 and 2050 (Figure 1.23). In the 2DS, investments will need to be ramped up considerably by 2020 in these regions to ensure that new building additions are energy efficient, thereby avoiding lock-in of long-lived capital investments. In OECD countries, additional investments for deep energy renovations of existing buildings likewise need to increase quickly by 2020, to ensure that aggressive energy efficiency improvements are achieved in the bulk of existing buildings by 2050 (requiring deep energy renovations of around 3% of existing buildings each year between 2020 and 2050).

Figure 1.23 Additional investment needs to 2050 in the buildings sector by region and period



Key point *Nearly two-thirds of additional investments are required in non-OECD countries to ensure that new building additions and equipment purchases are energy efficient.*

Key actions

Capturing the enormous energy savings potential to 2050 in the buildings sector would deliver a broad range of benefits, including lower electricity and fuel costs for businesses and households, greater reliability in meeting energy demand without costly infrastructure and vulnerability to grid disruptions, and reductions in CO_2 emissions and pollutants that pose a threat to human health. To achieve this, policy action is needed to promote building energy efficiency measures and to ensure that they are standard practice across the global buildings market.

26 Building infrastructure investments (e.g. construction of buildings, excluding energy efficiency measures and equipment purchases) are not included in this assessment. Energy-related building envelope renovation measures (e.g. occasional replacement of windows and mild levels of insulation and air sealing) are accounted for in the 6DS, while under the 2DS, costs for aggressive envelope measures for deep energy renovation and low-energy new building construction are assumed.

Governments need to work together and with key stakeholders to ensure that consumers and manufacturers maximise energy efficiency potential and limit the costs of future change by taking action today, particularly as most buildings and many building technologies have long lives. This is especially true in rapidly emerging economies, such as China and India, where there is a window of opportunity to ensure construction of high-efficiency new buildings over the coming decades, before the bulk of expected stock to 2050 is built. In OECD countries, significant effort is needed now to promote deep energy renovations in existing buildings, especially as it may take 10 to 15 years in some markets to ensure that deep energy renovation measures are viable, cost-effective and standard practice.

To achieve the full savings potential in buildings, a variety of policy measures are needed to put the buildings sector on track and achieve 2DS energy savings and emissions reduction objectives by 2050 (Table 1.1). In the near term, labelling and minimum performance standards for lighting, appliances, and heating and cooling equipment are needed in all countries to capture energy efficiency potential. Rigorous and prescriptive building codes are also needed for new construction in all countries. In the short to medium term, targets and incentives for very-low energy buildings will be necessary to send signals to consumers, building stakeholders and product manufacturers to help establish market demand. Over the medium to long term, more stringent standards, mandatory energy efficiency improvements of existing buildings, and continued development of advanced building technologies will all help ensure that 2DS energy targets are achieved.

Table 1.1 Policy areas for near-term action and long-term objectives

Policy action area	Near-term action (through 2025)	Long-term objective (2025 to 2050)
Whole building systems	Promulgate enforceable building codes in all regions and strive for near zero-energy buildings (nZEBs) in new construction. Implement policies to drive uptake in deep energy renovation in existing buildings.	Effect enforceable building codes in all regions with high energy performance standards (e.g. nZEBs or better) for all new construction and rigorous energy performance targets for existing buildings.
Building envelope*	Promote very high performance envelopes, including air sealing, insulation, highly insulating windows and cool roofs. Continue R&D for super thin insulation, dynamic glazing and whole envelope renovation packages.	Achieve highly insulated, integrated building envelopes (e.g. nZEBs or better) at negative life-cycle cost. Mandate minimum energy performance for building envelope components through enforceable building energy codes.
Space heating and cooling equipment	Increase promotion of solar thermal and heat-pump technology, with R&D for cold climates and gas thermal systems. Mandate condensing boilers for gas heating across all regions. Prohibit use of electric resistance heaters as main heating source.	Promulgate integrated energy solutions for heating and cooling with net-zero emissions. Mandate minimum performance standards above 120% efficiency for stand-alone gas heating equipment and above 350% for typical cooling equipment. Pursue low-cost solar cooling technologies.
Water heating	Encourage uptake of heat-pump water heaters and mandate condensing boilers or instantaneous systems for gas heating across all regions. Continue R&D on low-cost solar thermal systems.	Mandate minimum performance standards above 150% efficiency for electric stand-alone equipment. Achieve solar thermal systems that meet ≥75% annual water heating load.
Lighting	Ban all traditional incandescent and halogen light bulbs. Continue R&D and promotion of solid state lighting and other innovative designs.	Implement minimum lighting energy performance criteria above 100 lumens/watt.
Appliances and cooking	Implement and actively update minimum energy performance standards for appliances and equipment. Promulgate clean, energy-efficient cooking solutions for developing countries.	Bring to market highly efficient appliance technologies and mandate minimum energy performance standards for all electric plug loads including standby and networked power.

* For more information on building envelope technologies, R&D and energy performance targets, see www.iea.org/publications/freepublications/publication/technology-roadmap-energy-efficient-building-envelopes.html.

A systems approach that implements integrated policies in whole buildings or multiple buildings can facilitate synergies across different technologies and actors and result in capital cost savings. Effective policy is also needed at the individual component level within a systems approach to ensure that all market opportunities are realised.

Continued support for R&D is needed to bring advanced building products to market at cost-effective prices and to continue energy efficiency improvements across buildings sector technologies. This includes applying tighter minimum energy performance standards and applying market incentives and other policy measures to bring advanced technologies to full commercialisation. Collaboration among countries, academia and industry is essential to achieving this objective.

Finally, to develop more robust and targeted building energy policies, collection, consistency and comparability of data need to be improved. This requires capacity building in the governance and management of building energy data across countries. Collaboration among countries can also help to establish common definitions of key building metrics to improve understanding of global building performance and pathways to an energy-efficient, low-carbon buildings sector.

The Paris Agreement and clean energy technology development

The *ETP 2015* results ahead of COP21 in Paris showed that decarbonisation of the energy sector is achievable and economically sensible, but there is a need for greater support for technology innovation in order to accelerate the deployment of cost-effective clean energy technologies (IEA, 2015a; IEA, 2015c). The Paris negotiations led to agreement on an ambitious target to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C" (UNFCCC, 2015), as well as acknowledging the role of technology innovation in driving deep decarbonisation of the energy sector in line with IEA recommendations (Box 1.6). However, while realising the current pledges would have a tangible impact in curbing emissions, emissions would still be rising in 2030, whereas a near-term peak and then decline in emissions is needed to keep temperature rise below 2°C (IEA, 2015a). As this report shows, ambitious strategies to enhance low-carbon technology development across both the supply side and the demand side are needed to deliver the energy sector transformation consistent with the temperature goal below 2°C. The long-term goal of net zero emissions of GHGs in the second half of this century will, however, require considerable technological innovation.

Enhanced role for technology under the UNFCCC

There is more direct focus on technology innovation in the Paris Agreement than has been the case in any earlier climate agreement. The agreement acknowledges that accelerating, encouraging and enabling technology innovation is critical for an effective, long-term global response to climate change. It puts an increased emphasis on technology development, complementing the previous focus on technology transfer under the UNFCCC. This includes explicit focus on technology RD&D as well as the development of endogenous capacities and technologies in developing countries.

To deliver upon the enhanced ambition, the agreement established a "technology framework", which will provide overarching guidance to the existing technology mechanism, and provide a basis for creating enhanced links between the UNFCCC technology mechanisms with other UNFCCC bodies and non-UN technology actors. The role of the Technology Mechanism and its two arms, the Technology Executive Committee, with responsibility over technology policy guidance under UNFCCC, and the Climate Technology Centre and Network (CTCN), an operational arm for technology action, has equally been strengthened to support the implementation of the Paris Agreement, including through the NDC stock-take process.

Box 1.6

The Paris Agreement

The climate change agreement negotiated at COP21 in Paris represents a breakthrough in terms of enhanced global climate change mitigation and adaptation action. As a part of the agreement, countries agreed an objective to hold the increase in the global average temperature to well below 2°C.

The agreement is designed around bottom-up contributions towards GHG emissions mitigation submitted by countries, the NDCs. By the end of 2015, 160 pledges had been submitted, covering 187 countries and more than 95% of energy-related GHG emissions. NDC targets will be updated on a five-year basis and will be supported by a single methodological framework to account for GHG emissions and to track progress towards their achievement. There will be a formal global stocktake of progress in 2023 and every five years thereafter. As detailed in Chapter 2, the overall rate of development and deployment of clean energy technologies falls short of the 2DS. The NDCs are expected to drive demand for clean technology, and their implementation ought to work towards closing the technology gap to meet the 2DS.

The five-year cycle for taking stock of progress and revising NDCs is intended to create an opportunity for countries to raise mitigation ambition further as they gain experience and as technology costs reduce. In the agreement, countries are also encouraged to develop and communicate national long-term, low-carbon development strategies to link their short-term national actions with the collective goal of the Paris Agreement to peak global emissions as soon as possible and undertake rapid reductions thereafter.

The technology framework will also link results identified under technology needs assessments (TNAs) in developing countries to project implementation by building links with the UNFCCC's financial mechanism. Allocation of technology funding to developing countries should however be strategically devised and ought to ensure complementarity with the variety of bilateral and multilateral financial flows already in place. The CTCN has already commenced playing an important role ensuring the collaborative approach in TNA development and implementation, and enhancing its capacity to ensure that TNAs contain a clear business case will be essential.

While the details of the new technology framework are yet to be developed, it has the potential to be an important platform to bring together all actors within the energy technology innovation field. As there is an increasing number of technology innovation initiatives taking place outside the UN setting, broadening the access to the UNFCCC processes could provide considerable added value. Inclusive collaborative action between developed and developing countries can greatly enhance energy technology innovation capacity and adaptation of existing technologies within the local context.

To accelerate innovation in developing countries, it is also essential that solutions meet local technology development priorities and recognise local conditions and local innovation capacity. Enhancement of national systems of innovation for energy technology can develop a conducive environment for climate technology development and transfer. International collaboration should focus on the development of locally applicable technologies or alteration of existing technological solutions to suit local needs. The Paris Agreement specifically calls for collaboration on technology development at early stages of the technology cycle. Provision of financial support to developing countries for strengthening co-operation in both technology development and transfer at all technology stages should therefore follow suit.

The informal role that non-state technology actors have been playing under the UNFCCC was also formalised in the Paris decision, which explicitly recognises the importance of all actors in addressing climate change. It further committed to an ongoing process to highlight efforts of non-state actors and accelerate co-operative climate action between state and non-state actors, building on the Lima Paris Action Agenda (LPAA) at COP21. This specifically targeted mobilisation of further action in energy technology innovation through the LPAA Innovation Focus component.

Technology innovation and transformation outside the UN framework

Low-carbon energy technology innovation action during COP21, but outside the UNFCCC processes, matched the progress in the negotiations. Government and private-sector actors made extensive commitments to increase investments in RD&D in low-carbon energy technologies and ways to speed up their diffusion. The two principal initiatives were the government led Mission Innovation and the private capital-focused Breakthrough Energy Coalition (Box 1.7).

Box 1.7 Mission Innovation and the Breakthrough Energy Coalition

Mission Innovation (2015) is an open-ended initiative of 20 countries to dramatically accelerate public and private global clean energy innovation. Countries committed to double government clean energy RD&D investments in the sector over the next five years. As the 20 countries under Mission Innovation represent over 80% of global government RD&D expenditure in energy technology innovation, this represents a sizeable increase in investment. Under the associated private-sector Breakthrough Energy Coalition (2015), 28 investors from ten countries, led by the founder of Microsoft, Bill Gates, are committed to invest patient capital into early-stage low-carbon technology development. Building upon the government funding in basic and applied research in low-carbon energy technologies, the coalition aims to support the innovative ideas that come out of the public research pipeline and carry the projects through to commercial viability.

Accelerated deployment of cost-competitive low-carbon technologies and development of innovative technologies is critical to achieve emissions reduction in line with a 2°C goal, but current RD&D investment falls well short of the levels required to meet this long-term climate goal (IEA, 2015c). The combination of doubling government spending in the currently underfunded area of energy technology RD&D and effective private finance mechanisms that target viable projects, can plug the hole of the lacking investment.

Alongside substantial increases in finance for energy technology innovation, implementation efforts need to be co-ordinated to ensure that resources are allocated effectively (Box 1.8). Joint research partnerships among countries as well as between public and private sector can address regional technology innovation needs by developing tailored innovation programmes. Alignment of research objectives internationally and enhancement of collaborative work through multilateral partnerships will maximise the benefits from the mobilised investment.

Box 1.8 **Energy technology collaboration and the IEA Technology Collaboration Programmes**

There are already various multilateral international energy technology collaboration initiatives, including the IEA Energy Technology Network, Clean Energy Ministerial, Innovation for Cool Earth Forum and Low Carbon Technology Partnerships. It will be important to build upon these and streamline and synergise existing efforts to create truly global collaboration in energy technology innovation.

The IEA has a long track record in helping to build a supportive enabling environment for collaboration in technology innovation.

The IEA Technology Collaboration Programmes (TCPs), formerly known as the IEA Implementing Agreements, were established 40 years ago and now comprise around 6 000 participants from 51 countries. TCPs have both fed into and taken advantage of the multitude of tools developed by the IEA, which provide information on how technology innovation can contribute to achieving policy and business objectives. These tools have helped the IEA develop a unique capacity in terms of providing guidance, inputs and co-ordination for multilateral energy technology collaboration.

Collaborative initiatives can be used for setting common goals and objectives in specific technology areas, developing global, regional and national roadmaps to achieve the goal and identifying the outstanding issues to be addressed. Collecting and compiling information on countries' individual and collective efforts in low-carbon technology innovation can help determine whether a specific technology is on track in terms of its commercialisation. The existing and new initiatives can also assist governments, private investors and technology innovators by providing information needed to promote commercialisation and dissemination of clean energy technologies so they reach global market penetration. The commitment under Mission Innovation, that participating countries provide, on an annual basis, transparent, easily accessible information on their respective clean energy RD&D efforts, should be implemented and be extended to include key private-sector actors in the energy technology innovation field.

Policy action to lead the transition

Achieving the 2DS will require an unprecedented effort to develop and deploy low-carbon technologies and to effect behavioural changes that increase preferences for end-use services such as public transport. If impacts from climate change are to be limited and, at the same time, other energy sustainability objectives are to be achieved, energy policies need a structural, swift and no-regret change of direction now.

The ongoing debate and analysis on "what we should do" and "what we can expect" – i.e. the ideal solutions and the potential impacts of alternative strategies – are instrumental to implementing more efficient policies. However, such debate should not be an excuse for complacency to avoid facing the costs of transition. The additional investments to deploy the technology necessary to reduce carbon emissions are required in order to avoid what could be far larger costs to society over the long term. Scenario modelling and analysis carried out for the Nordic region (NER and IEA, 2016) shows that carbon neutrality can be achieved with additional regional investment costs amounting to a small fraction of the cumulative regional GDP over the period 2013-50 (Box 1.9).

Box 1.9 Nordic countries aim for carbon neutrality without compromising economic growth

Representing the world's 12th largest economy in nominal GDP terms, the five Nordic countries of Denmark, Finland, Iceland, Norway and Sweden all have ambitious climate targets for 2050. To realise a near-carbon neutral scenario by 2050 would require additional investments in infrastructure and energy efficiency of the order of 1% of cumulative GDP over the period. However, these investments are more than offset by fuel savings and avoided external costs related to the health impacts of air pollution. Increased energy security and other benefits will further strengthen the economic case for these investments.

Progress has and will continue to be driven by policy action and cross-border co-operation. Carbon taxation and regional grid integration have brought the carbon intensity of Nordic electricity supply to a level the world as a whole must reach in 2045 in order to realise the 2°C Scenario. The Nordic countries are improving energy intensity in buildings through some of the world's most stringent building codes, and reducing the carbon intensity of heat supply through low-carbon, advanced district heating networks. Decarbonisation of transport will require aggressive policy action and the majority of additional investments, but progress is already evident, as exemplified today by Norway's world-leading EV roll out. The Nordic industry sector is energy intensive and has a high share of process emissions, requiring the deployment of CCS or radical improvements in production technologies. In the power generation, heat, buildings and transport sectors, strong policies have and can continue to reduce emissions without compromising competitiveness; Nordic industry on the other hand is at greater risk of carbon leakage. Deft policies in the industry sector and international co-operation will be crucial in achieving these final steps towards a carbon-neutral Nordic energy system (NER and IEA, 2016).

Carbon pricing, removal of fossil fuel subsidies, market and regulatory frameworks aligned with long-term sustainability targets, increased public support for RD&D activities, and all other levers require swift adoption, but policy action is lagging behind, even to realise the easiest of these measures. For instance, implementation is required to increase confidence that a revenue-neutral carbon tax can actually lead to net positive macroeconomic effects. Overall, the 2DS is supported by many policy pillars, which need to be adapted to regional and national contexts to maximise the benefits of the transition.

However, even the 2DS might bring disruptive climate change impacts for some countries and regions. The negotiation process, as well as the outcome, of COP21 recognised this risk and called for stepping up efforts to an even more ambitious objective of limiting the long-term temperature increase to "well below" 2°C. With this momentum, the IEA proposes to focus the next edition of *ETP* on re-defining the climate goals to meet what may turn out to be one of the greatest challenges that humanity has faced: radically restructuring the world's energy system in only three decades to achieve carbon neutrality earlier than 2050.

Preliminary analysis indicates that to have at least a 50% probability of limiting the long-term increase to 1.5°C, the feasibility of ambitious low-carbon scenarios becomes even more important. Therefore, the proposed IEA analysis of the "well below" 2°C path will aim to address the most important questions on the role of technology and policy to meet this target. For instance, greater understanding is needed of whether relying only on the current technology "stock" – even accounting for a continuation of the technological trends that have been observed until now – can take the global energy system well below the 2°C goalpost without a significant increase in investments needed to achieve the additional carbon emissions reduction required. The transformation needed in the energy system to achieve such an ambitious objective might still rely on a similar low-carbon technology mix as for the 2DS, but deployed at a much faster rate. However, it is important to analyse the contribution of other options, such as accelerated technology innovation, which could not only continue to sustain linear improvements to existing technologies but also bring breakthrough energy technologies to technical and economic viability. Policy makers should therefore aim to bring radically innovative energy technologies to market. In addition, lifestyle changes could play an essential role in the "well below" 2°C path, and the potential impact of policy in shaping technology-related behaviours to drive this transition would also merit greater examination.

In sum, many levers are still available to policy makers. Recent policy commitments need to be translated into action at a fast pace not only to avoid the severe long-term economic costs of unsustainable patterns of energy use, but also to continue providing human development opportunities to large sections of humanity.

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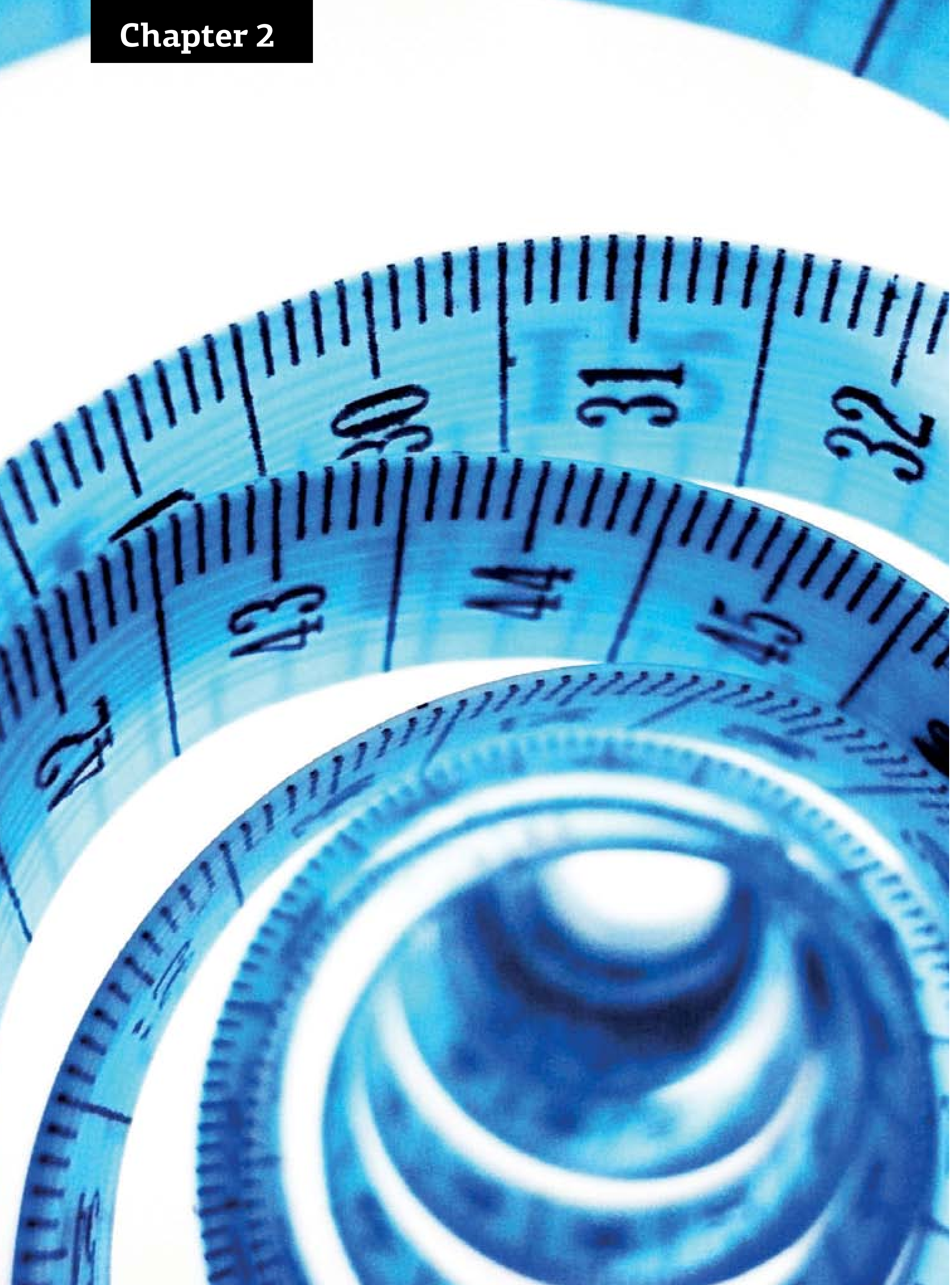
Chapter 2



Tracking Clean Energy Progress

Clean energy technologies continued their advancement as mainstream energy solutions in 2015. However, policy makers need to remain committed, to avoid a lowering of priorities due to low oil and coal prices at this critical time, to the transition to a decarbonised energy system.

Key findings

- ***The threshold of 1 million electric cars was crossed in 2015, with an overall annual sales growth rate of 70%.*** *While still small in absolute terms relative to the entire vehicle stock, this growth provides confidence in a viable alternative technology solution. Continual annual average growth of at least 39% is required to remain on track with the* Energy Technology Perspectives (ETP) *2°C Scenario (2DS) 2025 sales objective. This ambitious near-term objective seems achievable with sustained policy and funding support.*
- ***Renewable power generation grew by an estimated 5% in 2015 and now accounts for around 23% of total electricity generation globally.*** *New renewable electricity capacity grew at its fastest pace in 2015, supported by policies driven by energy security, local pollution concerns and climate benefits. With the momentum of the United Nations Framework Convention on Climate Change (UNFCCC) 21st Conference of the Parties (COP21) and recent policy changes, the outlook for renewable power is more optimistic. However, policy uncertainties, non-economic barriers and grid integration challenges persist, preventing renewables from being fully on track with the 2025 2DS target.*
- ***Nuclear power plant grid connections doubled in 2015.*** *Furthermore, progress and construction times in 2015 show the long-term 2DS targets to be more achievable than previously thought. However, several policy matters have the potential to impede the deployment of new nuclear power plants. In particular, more support is needed for the existing fleet to prevent early closures.*
- ***Further proof of the technical viability of carbon capture and storage (CCS) was demonstrated in 2015.*** *The current wave of CCS projects continued to move forward, with two new projects beginning operation in 2015. CCS has applications across both the power and non-power sectors, including in processes that may have no alternative for deep emissions reductions (e.g. cement, steel); however, progress is falling short, with no new investment decisions or advanced planning for projects in 2015. Industry and governments need to make significant investments in projects and technology development to get CCS on track to meet the 2DS target.*
- ***Energy efficiency improvements continued at a steady pace, with buildings and appliances improving at a faster rate than other end uses.*** *However, more aggressive measures are vital in the short term to stay on the least-cost pathway to meet 2DS targets and fulfil the role of energy efficiency as the largest contributor to greenhouse gas (GHG) emissions reductions under International Energy Agency (IEA) scenarios, and contribute to achieving energy-related emissions peaking in the short term.*

Opportunities for policy action

- *Despite low energy prices, strong action to eliminate fossil fuel subsidies – especially while oil prices are low – needs to happen in the short term. Fossil fuel subsidies create an uneven playing field for clean energy technologies. Eliminating fossil fuel subsidies would unlock significant financial resources that could be redirected to implementing existing cost-effective energy efficiency measures and investment in innovative clean energy solutions.*
- *Effective measures that can be implemented quickly in the short term include international and regional alignment on the stringency and coverage of minimum energy performance standards for appliances and equipment, such as building heating and cooling equipment, industrial motors, and vehicles. Widespread deployment of existing best available technologies to improve energy efficiency could yield significant annual savings.*
- *Decarbonising electricity generation is an imperative in order to meet 2DS targets. Final electricity prices need to reflect the environmental and other costs of fossil-based generation. Recognition needs to be given to the emissions reductions that clean energy generation can provide and the energy security and flexibility made possible by these resources, whether variable and distributed renewables or large centralised clean energy solutions such as nuclear and CCS.*
- *Incentives to increase the uptake of system integration technologies that closely match supply with demand and improve overall system performance are also needed, especially in countries and regions where the electricity grid is expanding.*
- *Energy market frameworks need to ensure uninterrupted investments in clean energy technologies. Broader integration of sustainable energy into policy and market frameworks, as well as strategic planning in all energy end-use sectors, are needed for sustainable development and to avoid lock-in to an inefficient energy future.*
- *To increase the deployment of renewables for both power and heat generation, governments need to eliminate persistent policy uncertainties, avoid retroactive policy changes, and address other issues such as financing, grid access and system integration by implementing well-established best practices.*
- *Policy attention and investment in research and development of clean energy solutions are essential in order to facilitate achieving long-term goals. The recent successes in proof of concept of CCS and energy storage solutions are a result of long-term innovation; however, in order to have continued advances in maturity and scale, sustained support is required. Enhancing international co-operation is a favourable way to achieve and accelerate innovation.*
- *Globally there needs to be more emphasis on improving data availability and coverage as well as the usage of clean energy technology indicators in order to understand the aggregate impact of progress made in the development and deployment of clean energy technologies. There are multiple ways to do so, and particularly encouraging is the move to track progress of Nationally Determined Contributions by the UNFCCC COP21, which will create demand for more detailed data and quantitative analysis.*

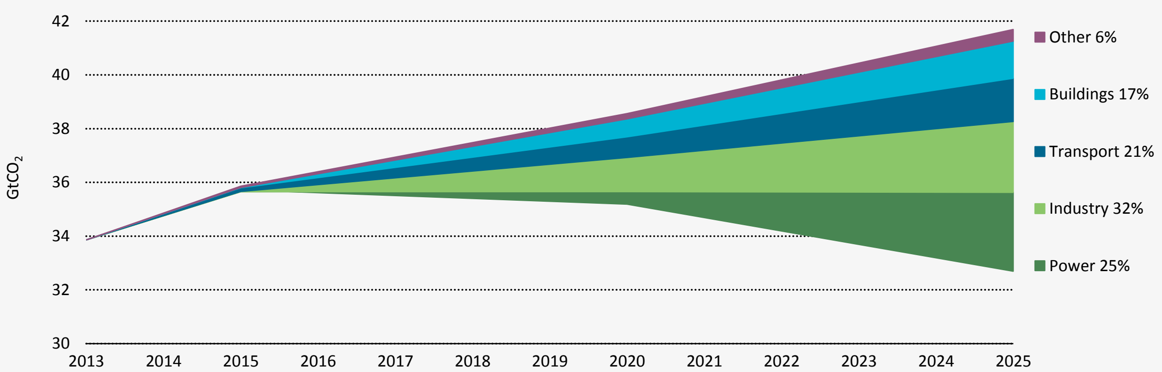
Tracking: How and against what?

Tracking Clean Energy Progress (TCEP) examines the progress of a variety of clean energy technologies towards interim 2025 2DS targets. Published annually, *TCEP* highlights how the overall deployment picture is evolving. For each technology and sector, *TCEP* identifies key policy and technology measures that energy ministers and their governments can take to scale up deployment, and drive efforts to achieve a more sustainable and secure global energy system.

TCEP uses interim 2025 benchmarks set out in the 2DS, as modelled in *ETP 2016*, to assess whether technologies, energy savings and emissions reduction measures are on track to achieve 2DS objectives by 2050. As in previous *TCEPs*, there is an evaluation of whether a technology or sector is on track, needs improvement or is not on track to meet 2DS targets. Where possible this "traffic light" evaluation is quantitative. There is also a short-term evaluation of progress in the most recent year for which data are available.

The report is divided into 18 technology or sector sections, and uses graphical overviews to summarise the data behind the key findings. The 2DS relies on development and deployment of lower-carbon and energy-efficient technologies across the power generation, industry, transport and buildings sectors (Figure 2.1).

Figure 2.1 Sector contribution to emissions reduction



Note: $GtCO_2$ = gigatonnes of carbon dioxide.

Key point *Reduction efforts are needed on both the supply and end-use sides; focusing on only one does not deliver the 2DS.*

For each technology or sector, *TCEP* examines under the headings of "recent trends", "tracking progress" and "recommended actions".

Recent trends are assessed with reference to the three *TCEP* measures that are essential to the success of individual technologies: technology penetration, market creation and technology development.

- Technology penetration evaluations include: What is the current rate of technology deployment? What share of the overall energy mix does the technology represent?
- Market creation examines what mechanisms are in place to enable and encourage technology deployment, including government policies and regulations. What is the level of private-sector investment? What efforts are being made to increase public understanding and acceptance of the technology? Are long-term deployment strategies in place?
- Technology developments discuss whether reliability, efficiency and cost are evolving and at what rate? What is the level of public investment in technology research, development and demonstration (RD&D)?

Tracking progress: For each technology or sector, progress towards 2DS objectives is evaluated.

Recommended actions: Policy measures, practical steps and other actions required to overcome barriers to 2DS objectives are identified.

Table 2.1 Summary of progress

	Status against 2DS targets in 2025	Policy recommendations
Renewable power ↗	With the improving competitiveness of a portfolio of renewable technologies and after the recent policy changes around COP21, the outlook for renewable power is more optimistic. Onshore wind and solar PV are on track to meet their 2DS targets but more effort is needed for other technologies to ensure renewable power is fully on track with 2DS.	■ Maintain or introduce further policy support and appropriate market design that enhance competition while sending clear and consistent signals to investors, notably long-term arrangements needed to de-risk investment in capital-intensive technologies. ■ Avoid any policy uncertainties – especially retroactive change – that can create higher risk premiums, undermining the competitiveness of renewables. ■ Take a holistic approach that maximises the value of a renewables portfolio to the overall system. Countries beginning to deploy variable power plants should implement well-established best practices to avoid integration challenges.
Nuclear power ~	Long-term policy and financial uncertainty remain for nuclear power, but significant increases in both construction starts and grid connections in 2015 helped make progress towards meeting 2DS targets.	■ Policy support is needed to encourage long-term operation of the existing fleet and construction of new plants, given their vital contribution to GHG emissions reductions, as well as their contribution to energy security. ■ Incentives such as carbon taxes or electricity market designs providing stable revenues may be required in liberalised markets, which otherwise favour lower-fixed-cost technologies.
Natural gas-fired power ~	The recent fall in coal prices relative to natural gas and falling electricity demand have curtailed growth in capacity and generation, making it difficult to gauge if natural gas-fired power would reach its 2DS potential.	■ To encourage coal-to-gas switching, electricity market incentives, such as carbon prices and more stringent regulation of plant emissions, are needed. ■ Electricity market mechanisms are needed that recognise natural gas-fired power's operational flexibility to support the integration of variable renewables.
Coal-fired power ~	Despite a slowdown in coal consumption globally, the projected trajectory of emissions reduction from coal is not on track to meet 2DS projections.	■ Where coal-fired capacity is expanding, policy measures are required to ensure assessment of the full range of lower-carbon generation options to satisfy new capacity. ■ Generation from the less-efficient subcritical coal units should be phased out and new coal-fired units should have efficiencies consistent with global best practice – currently supercritical or ultra-supercritical technology.
CCS ↗	Moderate progress in CCS was made in 2015. Significant investment in projects and technology development by industry and governments are needed to get CCS on track to meet the 2025 target of 541 million tonnes of carbon dioxide (CO_2) stored per year.	■ New projects need to be proposed and supported from development to operation to ensure a growing stream of projects through the development pipeline. ■ Investment in storage resource development will de-risk projects and shorten the development time. Storage characterisation and assessment are often the longest aspect of project development and outside the skill base of CO_2 capture project developers. ■ Continued research and development of CO_2 capture technologies are needed, including innovative technologies to reduce the costs and operational penalty of CO_2 capture.

On track?: ● Not on track ● Improvement, but more effort needed ● On track, but sustained deployment and policies required

Recent trends: ↘ Negative developments ~ Limited developments ↗ Positive developments

Table 2.1 Summary of progress (continued)

	Status against 2DS targets in 2025	Policy recommendations
Industry ~	Progress in industry continues, but the pace of improvements needs to increase to meet 2DS by 2025, bringing energy use to 12% and CO_2 emissions to 16% below the current trajectory by 2025.	■ Incentivise fuel switching, energy efficiency and deployment of best available technologies (BATs) in all industrial sectors by valuing these developments via international co-ordination and long-term stability on carbon-pricing mechanisms and energy taxation. ■ Encourage efficient use of all resources, and enable integrated, cross-sectoral benefits through sustainable diversification of production. ■ Create frameworks for co-operative, co-ordinated international and public-private efforts to accelerate development of innovative technologies globally.
Aluminium ~	Though progress has been made in improving energy intensity, continued demand growth will make 2DS increasingly difficult to attain without major technological innovations and renovations.	■ Prioritise recycling and material efficiency through all steps in the product chains. ■ Encourage producers to upgrade to BATs, make continual improvements to optimise equipment operation and phase out outdated equipment, such as Søderberg smelters. ■ Engage all stakeholders to support development of alternative process technologies, such as inert anodes, to reach deeper emissions reductions for the long term.
Transport ~	Transport emissions have increased at a rate of 1.9% per year over the last decade. To meet 2DS targets, emissions must peak and begin to decline within the coming decade.	■ Policies must raise the costs of owning and operating transport modes with high GHG emissions intensity. ■ Fuel subsidies must be phased out and emissions-based fuel taxes established. ■ Vehicle taxes must also be levied according to vehicles' emissions intensity performance, with monitoring and enforcement to ensure that the purported performance levels are being achieved. ■ Fiscal policies must be supplemented by other national (e.g. emissions and fuel economy standards) and local (e.g. parking and congestion pricing, public transport investment) measures.
Electric vehicles ↗	Electric cars have the potential to displace internal combustion engine (ICE) cars in the context of sustained RD&D, together with differentiated vehicle taxes and fuel taxes that incorporate social costs of GHG emissions.	■ Continued RD&D support is needed to hasten the milestone year when purchase costs of electric cars with all-electric ranges capable of accommodating most driving needs reach parity with ICE cars. ■ Governments must also prioritise comparative policy analysis and market research focusing on consumer preferences. ■ Differentiated vehicle taxes (such as "feebates") and high fuel taxes align the private and social costs of vehicle ownership, thereby closing the gap between purchase cost parity of electric and ICE cars.
Aviation ~	While recent annual average fuel efficiency improvements of 3.9% have exceeded aviation industry targets, meeting targeted fuel efficiency improvements beyond 2020 of 2% per year to 2050 will become increasingly challenging.	■ The introduction of CO_2 taxes on aviation fuels and mobilisation of investments for the development of high-speed rail networks would contain activity growth. Carbon taxes will be needed to promote fuel efficiency improvements exceeding International Civil Aviation Organization's targeted 2% annual improvement rate. Achieving the CO_2 emissions reductions targeted by the Air Transport Action Group would most likely require the introduction of biofuel mandates or other market-based incentives.

On track?: ● Not on track ● Improvement, but more effort needed ● On track, but sustained deployment and policies required

Recent trends: ↘ Negative developments ~ Limited developments ↗ Positive developments

Table 2.1 Summary of progress (continued)

	Status against 2DS targets in 2025	Policy recommendations
Biofuels (red: Not on track; ↗ Positive developments)	Modest growth rates (2% per year) in global conventional biofuels production and the early stage of development in the advanced biofuels sector have resulted in a downward revision of the contribution of biofuels within the 2DS.	■ Ambitious and long-term targets are needed for the transport sector relating to emissions reductions, shares of renewable energy and phasing out fossil fuels. ■ Widespread and strengthened advanced biofuel mandates or alternative policies that stipulate reductions in the carbon intensity of transportation fuels should be considered. ■ Financial de-risking measures may be needed to facilitate advanced biofuel production capacity investment. ■ Biofuels policies are needed that work within suitable governance frameworks to ensure that environmental, social and economic sustainability impacts are avoided.
Buildings (red: Not on track; ↗ Positive developments)	Current investment in buildings energy efficiency is not on track to achieve the 2DS targets. Globally, buildings energy performance (per square metre) needs to improve from a rate of 1.5% per year in the past decade to at least 2.5% per year over the next decade to 2025.	■ All governments need to develop rigorous and enforceable building energy codes and performance criteria for both new and existing buildings. ■ Effective policies and financial incentives are needed to leverage aggressive energy efficiency action in buildings to establish market demand. ■ Near-zero and zero-energy buildings should be promoted across all regions with supporting incentives and energy performance standards for very-high performance building products and equipment.
Building envelopes and equipment (red: Not on track; ↗ Positive developments)	Progress on adoption and enforcement of building energy codes and equipment energy performance standards is promising, but action has to date not kept pace with buildings sector growth. Deep energy renovations of existing buildings are not on track to achieve the recommended 2% to 3% annual building renovation level.	■ Policy makers should continue to develop, adopt, enforce and review building energy codes and standards to improve the energy efficiency of new building construction. ■ Governments need to promote deep energy renovation of existing building stock during normal refurbishment, including deep energy retrofits in public buildings to demonstrate the potential and economic value of these renovations. ■ Labelling and minimum performance standards for building components need to be enforced to accelerate the deployment of energy-efficient technologies, including financial incentives for very-high-performing products to increase adoption of BAT.
Appliances and lighting (orange: Improvement, but more effort needed; ↗ Positive developments)	The global coverage of energy efficiency standards and labelling programmes has increased (more than 80 countries, covering more than 60 different types of appliances and equipment), but further efforts are needed.	■ Increase coverage and stringency of energy efficiency standards, and increase effectiveness of labelling. ■ Phase out inefficient technologies such as halogen lamps. ■ Increase international and regional alignment where possible. ■ Develop policies and approaches aimed to reduce miscellaneous electric loads.
Solar heating (red: Not on track; ~ Limited developments)	Solar thermal heating has the potential to contribute to decarbonising the heat sector, but if recent trends in challenging economics, inadequate support and non-economic barriers continue, deployment will not progress fast enough to meet the global 2DS target.	■ Government efforts should focus on increasing the economic attractiveness across all solar thermal market segments such as providing adequate and consistent incentives over a predictable period of time and promoting innovative business models aimed at reducing high up-front costs. ■ Successful policies that set targets, mandate obligations and raise public awareness of solar thermal technologies should be replicated to create an enabling environment for solar heat.

On track?: ● Not on track ● Improvement, but more effort needed ● On track, but sustained deployment and policies required

Recent trends: ↘ Negative developments ~ Limited developments ↗ Positive developments

Table 2.1 Summary of progress (continued)

	Status against 2DS targets in 2025	Policy recommendations
Co-generation and district heating and cooling (~)	Shifts away from conventional, inefficient power generation are critical to achieving 2DS targets, and combined heat and power with modern, efficient district heating and cooling (DHC) systems can help reduce primary energy demand and improve overall system efficiency.	■ Mapping of heating and cooling opportunities across the energy economy can identify potential synergies and technology choices in electricity and heat generation and identify cost-effective opportunities to develop DHC networks in a more efficient, integrated energy system. ■ Policy measures are needed that facilitate investment in modernising and improving existing DHC networks to make them more energy efficient and maximise opportunities to use low-carbon energy sources as well as industry excess heat recovery. ■ Policy makers should remove market and policy barriers that prevent co-generation and DHC from competing as efficient and low-carbon solutions, such as high up-front investment costs, inflexible business structures, and lack of long-term visibility on policy and regulatory frameworks.
Smart grids (~)	Growth in smart-grid technologies decelerated in 2014, driven by market saturation and uncertainty in some key markets. Smart-grid technologies leveraging information technology solutions compensated for the stagnant growth in physical network assets.	■ Adapt regulations to capture the value of smart-grid investments in cost and performance targets of network owners and operators. ■ Encourage widespread adoption of standards and interoperability throughout the smart-grid value chain. ■ Increase awareness of cybersecurity and data ownership issues to prepare for widespread deployments.
Energy storage (↗)	Rapid cost reductions, accelerated deployment pace and specific policy action would justify a green rating. Sustained deployment and policies are required to maintain these trends.	■ Adapt market and regulatory frameworks to maximise value from storage deployments. ■ Diversify RD&D of storage technologies beyond lithium ion chemistries. ■ Promote training and capacity-building programmes for grid integration of storage.

On track?: ● Not on track ● Improvement, but more effort needed ● On track, but sustained deployment and policies required

Recent trends: ↘ Negative developments ~ Limited developments ↗ Positive developments

Renewable power

● Improvement needed
↗ Positive developments

Renewable power capacity grew at its fastest pace in 2015, supported by policies driven by energy security, local pollution concerns and climate benefits. With ambitious pledges put forward for the 21st Conference of the Parties (COP21) and recent policy changes in various countries, the outlook for renewable power is more optimistic than the forecast presented in the International Energy Agency (IEA) *Medium-Term Renewable Energy Market Report* (*MTRMR*) in October 2015 (IEA, 2015a). However, further policy action is needed to tackle both economic and non-economic challenges to deployment and put renewable power on track with the *Energy Technology Perspectives* (*ETP*) 2°C Scenario (2DS) target.

Recent trends

In 2015, global renewable electricity generation rose by an estimated 5% and accounted for around 23% of the overall generation. The People's Republic of China (hereafter "China") remained the largest market, accounting for an estimated 23% of global renewable electricity generation in 2015, followed by the European Union (17%) and the United States (US) (11%).

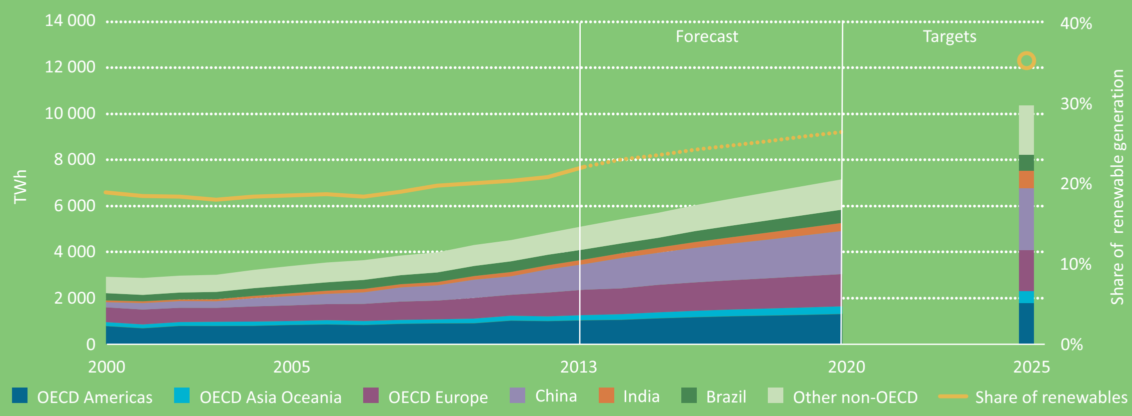
In 2014, net additions to grid-connected renewable capacity grew at their fastest pace, with 130 gigawatts (GW) installed globally. Early estimates show that this growth could be even higher in 2015, marking another record. In 2015, around 40% of new renewable additions came from onshore wind, with the commissioning of an estimated 60 GW of new grid-integrated capacity. China installed more than half of global onshore wind additions (33 GW), as developers rushed to commission their projects by January 2016 so as not to be affected by the feed-in tariff (FIT) reduction. The European Union added around 10 GW, which was slightly lower than 2014 additions, as lower capacity came on line in Germany. The United States added close to 8.5 GW, followed by Brazil (2.7 GW) and India (2.3 GW).

Solar photovoltaic (PV) capacity grew by 45-50 GW in 2015. China (15 GW) and Japan (11 GW) together represented more than half of this growth. New additions in the United States were 15% higher than the previous year, with around 7.3 GW installed. In the European Union, solar PV annual installations increased by around 10% to 7.5 GW. This new capacity was led by the United Kingdom (3.6 GW) Germany (1.3 GW) and France (1 GW). The expansion of solar PV in India picked up and reached 2 GW last year.

Hydropower additions are estimated to decrease for the second consecutive year since 2013, with fewer new capacities installed in China (19 GW including pumped-storage capacity) and Brazil (2 GW). Offshore wind annual deployment marked a new record, with over 3 GW connected to the grid, as a number of delayed projects in Germany became fully operational. Two large solar thermal electricity projects came on line, one in the United States (Crescent Dunes – 110 megawatts [MW]) and one in South Africa (KaXu Solar One – 100 MW). In 2015, the annual new installed capacity for bioenergy for power almost doubled, with major capacity coming on line in China, India and Thailand, while geothermal additions were around 300 MW.

Renewable costs, especially solar PV and onshore wind, have fallen dramatically in recent years. From 2010 to 2015, indicative global average onshore wind generation costs for new plants fell by an estimated 30% on average, while costs for new utility-scale solar PV declined by two-thirds. Over 2015-20, new onshore wind costs are expected to decline by a further 12%, while new utility-scale solar PV will decline by an additional quarter. These cost reductions are in line with the *ETP* 2025 targets. For offshore wind, costs have been increasing over the past few years as the majority of projects are being installed farther from the coasts and in deeper water. However, the results of the recent tender in Denmark and the contract for difference in the United Kingdom for projects that will come on line over 2018-20 have already shown a cost reduction potential

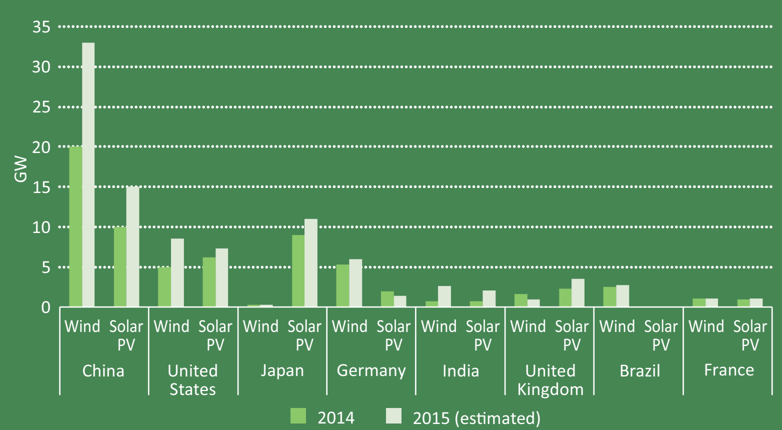
2.2 Renewable power generation by region



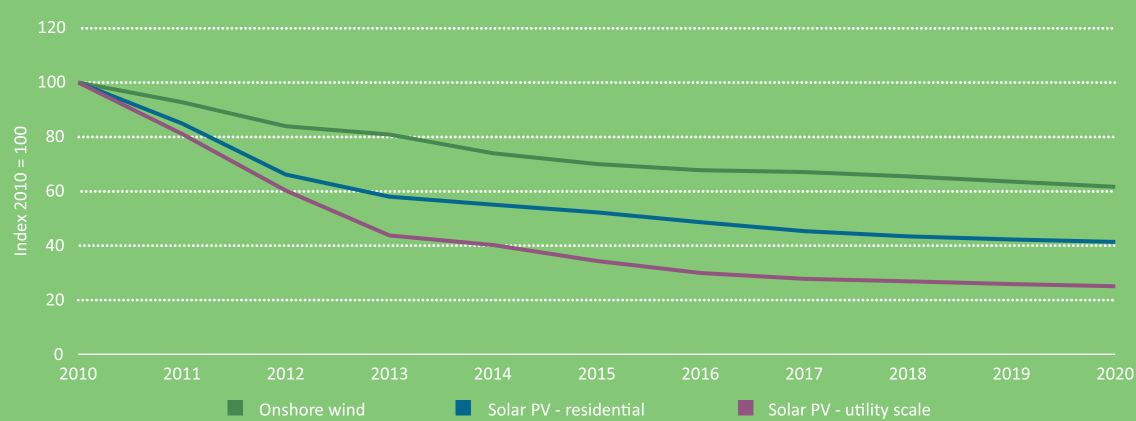
65%

AVERAGE COST DECLINE FOR UTILITY-SCALE SOLAR PV FROM 2010 TO 2015

2.3 Wind and solar PV additions



2.4 Indexed levelised cost of electricity



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up to 20%, compared with similar projects awarded three to five years ago.

The cost-effectiveness of some renewable options has improved because of a combination of sustained technology progress, expansion into newer markets with better resources, and better financing conditions, often supported by market frameworks based on price competition for long-term power purchase agreements (PPAs). Recently announced long-term remuneration contract prices offer evidence of such indicative forecast costs and suggest even lower generation costs are possible in the next few years. New onshore wind can be contracted today in a number of countries at USD 60/MWh-USD 80/MWh, with the best cases closer to USD 50/MWh (e.g. Brazil, Peru, Egypt and some US states). Meanwhile, new utility-scale solar PV projects can be contracted at USD 80/MWh-USD 100/MWh (e.g. France, Germany and Uruguay), with the best cases at around USD 60/MWh (e.g. Chile, Peru, United Arab Emirates, Jordan, South Africa and some US states).

While onshore wind and solar PV have not yet achieved widespread competitiveness versus fossil fuels, these benchmark cost ranges are comparable in some countries and regions with generation costs from gas, even in the current fuel price regime. In countries such as Australia, Brazil, Chile and South Africa, onshore wind can represent a more cost-effective source of new generation than fossil fuels. However, these cost trends do not automatically imply that solar PV and onshore wind are fully competitive. Competitiveness also depends on the value of the generation, where and when it is produced, and the system costs associated with integrating higher shares of variable renewables.

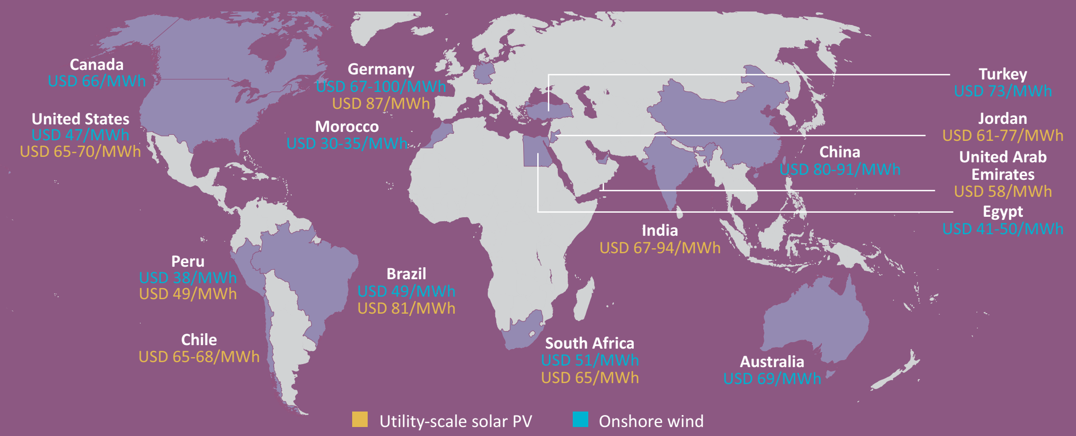
Over the last year, 160 Intended Nationally Determined Contributions (INDCs), representing 188 countries accounting for about 97% of global emissions, were submitted both before and after the COP21 meeting. More than 90 parties outlined renewable energy as a priority area with high mitigation potential, while more than 40 countries highlighted renewable electricity as part of their greenhouse gas (GHG) reduction strategy. Of the Organisation for Economic Co-operation and Development (OECD) countries, Japan, Australia, Chile, Israel, New Zealand and Turkey introduced renewable electricity targets in their INDCs. In non-OECD countries, Brazil announced its intention to increase the share of non-hydro renewables in power generation to 23% by 2030, from around 9% today. India's INDC pledges to increase its solar capacity twenty-five-fold to 100 GW and to more than double wind capacity to 60 GW by 2022. In addition to those highlighted in INDCs, many more countries announced new renewable power targets, both ahead of and after COP21. France's "energy transition law" set a new goal of 40% renewable power by 2030. The United States pledged to increase the share of renewables in electricity generation (excluding hydropower) from 7% to 20% by 2030.

Overall, policy remains vital to achieve these ambitious targets because it has a direct impact on the attractiveness and deployment of renewables. Over the last year, some positive developments have taken place to address renewable policy uncertainties in various countries. In the United States, the production tax credit (PTC) for onshore wind was extended through the end of 2019, but will be progressively reduced from 2017. For other renewable energy technologies (geothermal, municipal waste, landfill gas, and open- and closed-loop biomass), the PTC was only extended through the end of 2017. The investment tax credit (ITC) was extended through to 2022 for utility-scale solar PV, but it will gradually decrease in 2020 from 30% to 26%; to 22% for facilities starting operation in 2021; then dropping to 10% for utility and commercial applications. For residential systems, the ITC will be phased out through 2021 following the same schedule. These extensions are expected to give a longer-term visibility to renewable energy developers, lifting a major policy uncertainty and accelerating deployment.

In September, Mexico released rules for electricity and clean energy certificate markets, which included the schedule of renewable auctions with long-term PPAs that will be awarded in 2016. In France, the enactment of the "energy transition law" is expected to facilitate the deployment of renewable energy projects with strong binding targets, as well as the introduction of new zoning and permitting regulations. In Latin America, recent changes in the auction design in Chile have enabled wind and solar PV to be part of annual energy tenders offering lower prices than fossil fuel alternatives.

Not all policies introduced over the last year were supportive to renewable deployment. For instance, in the United Kingdom, the government decided to cut the FIT for both small-scale solar PV and large onshore wind projects. The Department of Energy and Climate Change (DECC) also confirmed that it will end support for all new solar farms supported through the Renewables Obligation. Having approved a renewable energy law in April 2015, replacing the green certificate scheme with

2.5 Long-term contract prices for 2016-19 project commissioning



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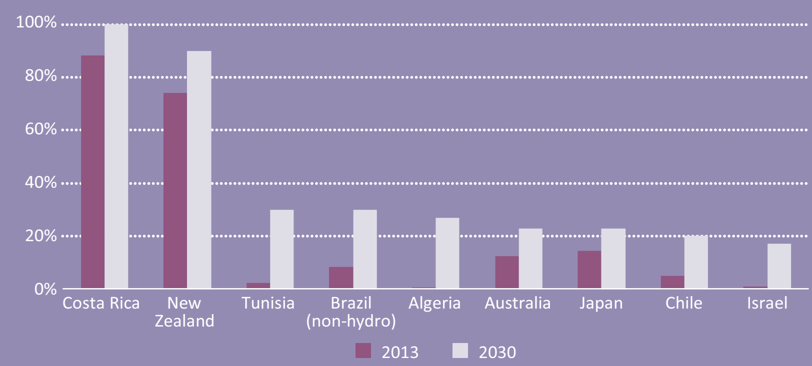
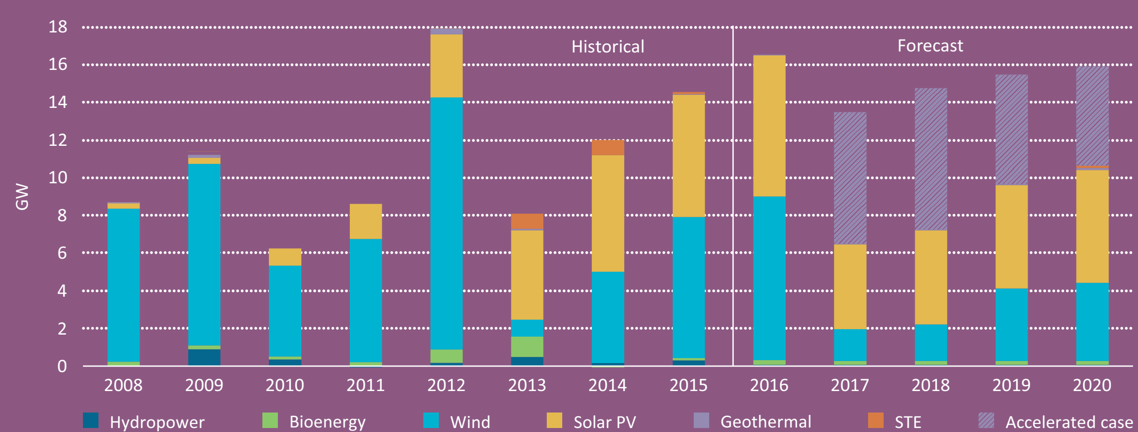
COUNTRIES HIGHLIGHTED RENEWABLE ELECTRICITY AS PART OF THEIR GHG REDUCTION STRATEGY IN THEIR INDCS

2.6 Renewable power generation goals in selected INDCs



2.7 Projected impact of US federal tax policy change on capacity additions



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auctions, the Polish government decided in December 2015 to postpone the implementation of the law for six months. In Nevada, the Public Utilities Commission approved a new net metering policy that changed remuneration of excess electricity from the retail to the wholesale rate, for both existing and new projects.

Tracking progress

Renewable electricity generation is expected to grow by over 30% between 2014 and 2020, reaching 7 300 terawatt hours (TWh), and is currently at risk of falling short of the 2DS target of 10 340 TWh by 2025. This result is subject to strong regional differences across technologies and regions.

Solar PV is fully on track to meet its 2DS power generation target by 2025. Its forecast is more optimistic over the medium term, reflecting more optimistic growth prospects and expectations of improving economics. The growth should be robust in OECD countries, with decreasing annual additions in Europe compensated by strong expansion in the United States, Chile, Japan and Mexico. In non-OECD countries, growth of solar PV should continue spreading geographically. Deployment trends in China are strong, owing to improving economics and growing distributed generation opportunities. If these medium-term trends continue, solar PV could even surpass its 2025 target.

Onshore wind, the second-largest renewable technology, is also on track. In OECD countries, the outlook in the United States is more optimistic after the long-term extension of the PTC. However, grid integration and policy uncertainty challenges persist, especially in the European Union and Japan. Doubts over governance of the European Union's 2030 climate change goals and recent policy changes in the United Kingdom and Poland are expected to affect the deployment. In non-OECD countries, onshore wind is expected to grow fast, especially in China, Brazil and India. However, integrating large amounts of new onshore wind power remains a challenge, especially in China and India.

For offshore wind, OECD countries, particularly in Europe, are expected to lead deployment driven by cost reductions and grid connection improvements. With this prospect, OECD countries are on track to meet their 2DS targets. Deployment is still falling behind in non-OECD countries, especially in China, as investment costs remain high and technological challenges persist.

Hydropower needs improvement to reach its 2DS generation target. Over the medium term, new additions of hydropower capacity are expected to fall in OECD countries, mainly due to decreasing resource availability. In non-OECD countries, new additions are expected to be strong, with great potential still available in Asia and Africa. However, environmental concerns and lack of financing pose challenges to large-scale projects. In China, annual growth of hydropower is expected to slow down due to similar challenges.

High investment costs for solar thermal energy (STE) are slowing the pace of deployment. The potential for electricity generation from geothermal energy remains largely untapped. However, pre-development risks remain overall high. For biomass, sustainability challenges and long-term policy uncertainty have been affecting the economics of large projects, particularly in OECD countries. Ocean power is still at the demonstration stage, with only small new projects deployed mostly in Europe and North America.

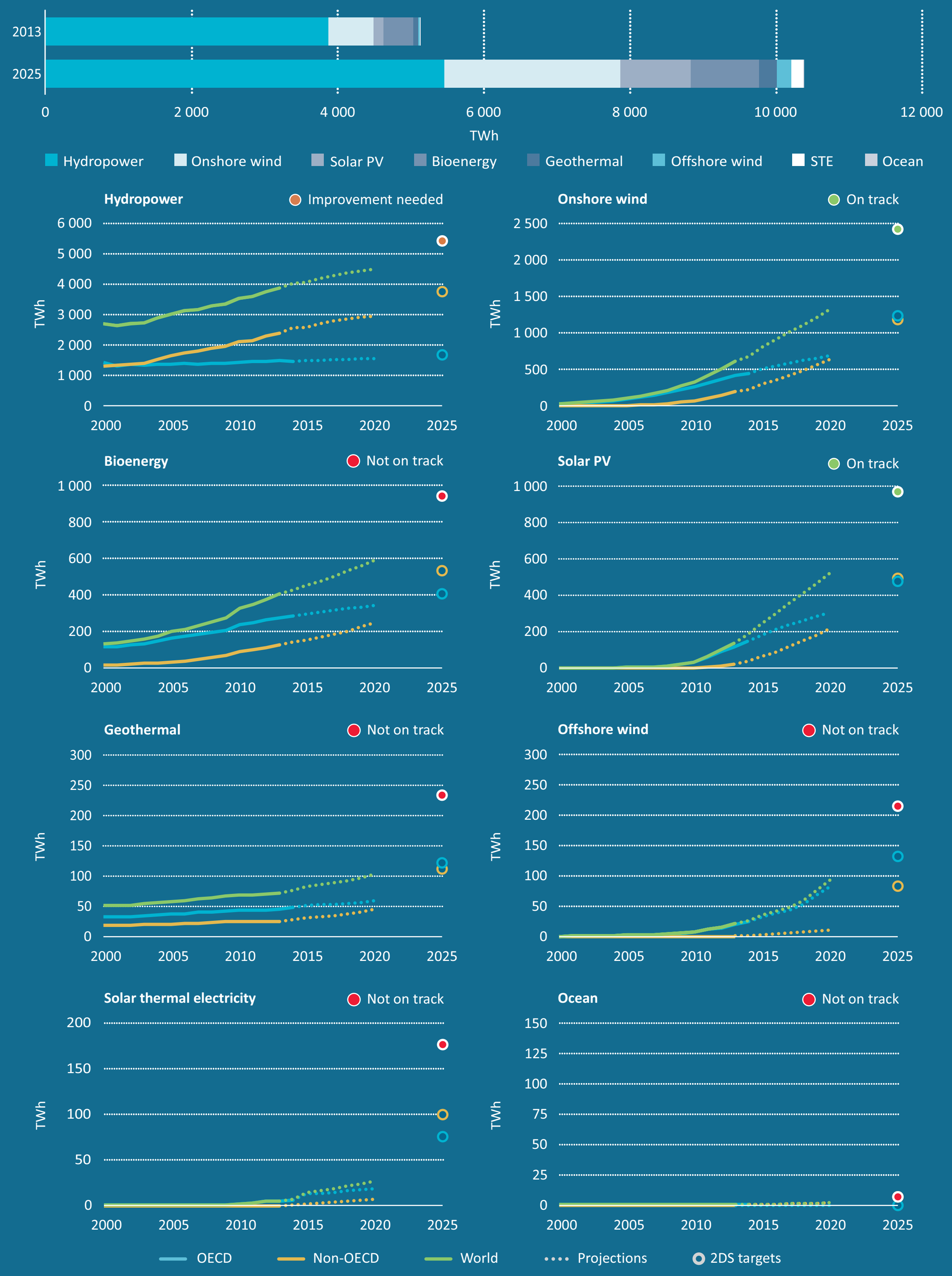
Policy recommendations

The drivers for renewables – energy security, local pollution reduction and decarbonisation – remain robust, supporting record-level deployment in both 2014 and 2015 in the power sector. This growth is underpinned by dramatically falling costs for renewable power in many parts of the world, driven also by policies that have enhanced competition and have provided long-term revenue streams. Countries should learn from factors that have led to lower remuneration levels.

Targets and policies announced before and after the COP21 meeting in Paris are expected to enhance deployment. Achieving the objectives of COP21 will, however, require policy makers to send clear and consistent signals, and maintain policy support and appropriate market design. Any policy uncertainty can create higher risk premiums, which directly undermine the competitiveness of capital-intensive renewables.

Countries beginning to deploy variable renewable power plants should implement well-established best practices to avoid integration challenges. Markets where variable renewable penetration is already high should take advantage of their existing flexibility assets, and consider other flexibility mechanisms to optimise the balancing of their overall energy system.

2.8 Renewable power generation by technology



For sources and notes see page 124

Nuclear power

● Improvement needed
~ Limited developments

Global nuclear generation continued to increase gradually. At the end of 2015, 67 reactors were under construction. Construction starts rose again in 2015 to seven units, up four from 2014, and the number of grid connections doubled from five in 2014 up to ten in 2015.

Recent trends

Perhaps the biggest nuclear news of 2015 was the restart of the first two reactors in Japan under the new regulatory regime set up following the accident at Fukushima Daiichi in 2011. Sendai 1 and 2 restarted, becoming the first two reactors in Japan to receive full safety and local government approval, successfully navigating the new regulatory and approval process. Additional units are preparing to restart in early 2016. China is by far the leader in new plant construction, connecting 14 reactors to the grid in the last three years with an average construction time of 5.5 years. Another 24 units are currently under construction, including three Hualong One reactors – a domestic advanced reactor design that China is looking to market worldwide.

Several policy matters have the potential to impede the deployment of nuclear power. India's 2010 Civil Liability for Nuclear Damage Act, which allows the operator recourse against suppliers under certain circumstances, is still a matter of concern, in spite of the establishment in 2015 of a nuclear insurance pool. Commercial negotiations are ongoing with a number of reactor vendors, but no firm contract has been signed. In July 2015, the French Parliament passed a new "energy transition" bill aimed at reducing carbon emissions across the energy sector. Although the French electricity mix is virtually decarbonised (74% nuclear, 13% hydro, 3.8% wind and solar [IEA, 2015b]), the bill also sets a target of reducing the share of nuclear electricity to 50% by 2025. This generation is to be replaced by renewables (with backup technologies, presumably gas), leading to an increase in carbon dioxide (CO_2) emissions from the power sector.

In the United States and Europe, reactor operators continue to re-evaluate the continued operation of nuclear power plants in deregulated markets, claiming that the importance of large, base-load power from non-emitting sources is not being recognised in the market pricing mechanisms. In the United States, Entergy announced it would shut down the Pilgrim plant in 2019, though it has a licence to operate until 2032, and later announced it would also shut down its FitzPatrick plant in New York. In Sweden, Vattenfall announced the earlier-than-anticipated shutdown of Ringhals 1 in 2020 and Ringhals 2 in 2019, instead of 2025, and E.ON announced the immediate shutdown of Oskarshamn 1 and 2 initially due to shut down between 2018 and 2020. These utilities blame low wholesale electricity prices, the burden of Sweden's tax on nuclear power and the cost of upgrading the plants.

At the same time, Électricité de France's Hinkley Point C plant in the United Kingdom seems to have found a financing option that other countries with liberalised electricity markets may decide to follow; its guaranteed pricing contract for difference (CfD) agreement having withstood legal challenges to date. In 2015, Finland became the first country to licence construction of a permanent repository for high-level waste.

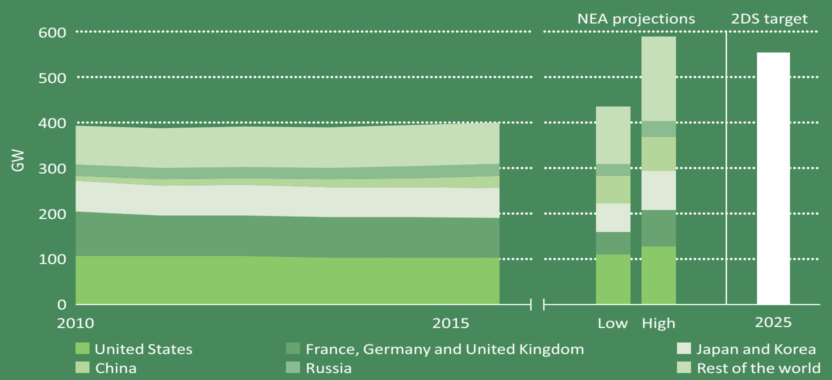
Tracking progress

According to the most recent *Red Book* (NEA and IAEA, 2014), gross installed capacity is projected to reach 438-593 GW by 2025, up from the current 403 GW; in the 2DS, global nuclear capacity would need to reach 553 GW by that time. Several nations, including China, have announced ambitious nuclear power expansion plans as part of their clean energy goals, which will be necessary to meet the 2DS targets.

Recommended actions

The realisation that swift action is needed to reduce GHG emissions and air pollution from fossil-based generation has highlighted again the potential of nuclear power to help meet these challenges. This awareness has yet to be translated into policy support for long-term operation of the existing fleet to prevent early closures of safe, reliable low-carbon base-load power plants, and facilitate construction of new units. Market incentives – in the form of carbon taxes or electricity market arrangements, or both – are needed to favour all low-carbon technologies.

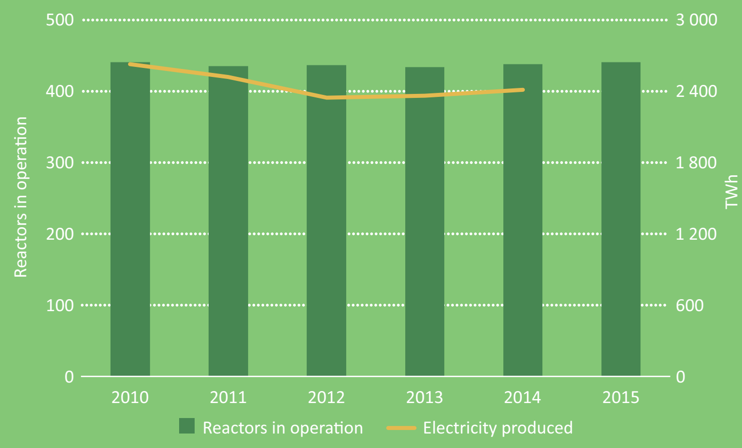
2.9 Installed gross nuclear capacity



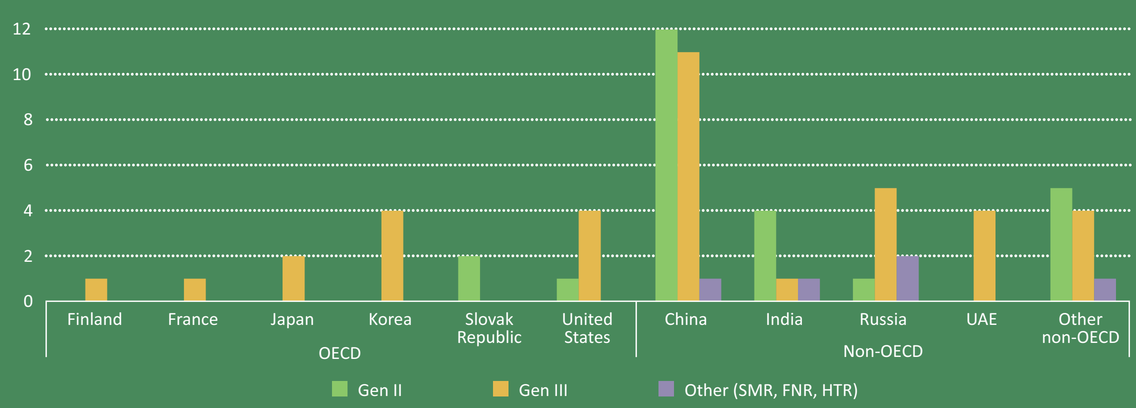
9 GW NEW CAPACITY CONNECTED IN 2015

2 400 TWh ELECTRICITY GENERATION FROM NUCLEAR IN 2014; THE SECOND LARGEST LOW-CARBON SOURCE AFTER HYDROPOWER

2.10 Operable reactors and electricity production



2.11 Reactors under construction



For sources and notes see page 124

Natural gas-fired power

Improvement needed

~ Limited developments

Natural gas-fired power generation accounted for 21.7% of total global power generation in 2013 (5 066 TWh), a year-on-year decrease of 0.4%. The recent fall in coal prices relative to natural gas, the rising generation from renewables, as well as falling electricity demand have curtailed the growth in capacity and generation of natural gas-fired power.

Recent trends

Following an increase of 2.2%, global natural gas demand reached around 3 500 billion cubic metres (bcm) in 2013, while demand in 2014 showed a small year-on-year decrease of 0.7%. In 2014, natural gas demand in OECD countries decreased by 2.3% over the previous year, while gas demand for power generation decreased by 1.5%, mainly owing to slow electricity demand growth and a continued and robust deployment of renewables. In contrast, natural gas demand in non-OECD economies increased by 0.8%, albeit less than the 2% or higher increases of recent years. Apart from the fall in coal prices relative to natural gas, policies that favour coal use in many Asian countries have been considered the main cause of falling gas demand. Nonetheless, the main contributor to the rise in gas demand in non-OECD economies was power generation, for which gas consumption increased by 33 bcm (4.1%). For example, Mexico's power sector gas demand rose to 41 bcm in 2013, up 34% on the previous year, and in 2014, natural gas plants made up 47% of Mexico's total power generation capacity.

In 2014, gas production in the OECD rose by 2.2% year-on-year, which was mostly driven by the United States (+5.9%) and Canada (+3.8%). In 2013, Canada added 1.6 GW of gas-fired power generation capacity, the highest among OECD countries, while in the United States, the particularly cold winter of 2014 was believed to have resulted in a gas demand rise of 18.4 bcm. The contribution from the two countries offset a substantial decrease in Europe (-7.5%). In Japan, gas-fired generation replaced roughly two-thirds of lost nuclear output from the Fukushima Daiichi accident, pushing its liquefied natural gas (LNG) imports up by about 29.9% between 2010 (the year before the accident) and 2014.

In China, natural gas prices have twice risen sharply since its gas pricing reform in 2013. As a result of the higher price, gas usage increased by less than 4% in 2014, despite 10 GW of new gas-fired generation capacity being added. However, the drop in oil prices from the last quarter of 2014 brought an opportunity to narrow the price gap between coal and gas, which made gas an increasingly attractive option from an environmental viewpoint. China is, however, scaling back its recent ambitious targets for domestic shale gas production. In 2013, it produced around 3 bcm of coalbed methane, 0.2 bcm of shale gas and around 45 bcm of tight gas.

In non-OECD economies outside China, 2013 saw increased gas demand in the power sector registered in Saudi Arabia (5.6 bcm) and Brazil (5.4 bcm). In India, however, high costs of imported LNG and relatively low electricity prices in 2014 saw the utilisation rate of India's 22 GW of gas generation capacity barely rise above 20%.

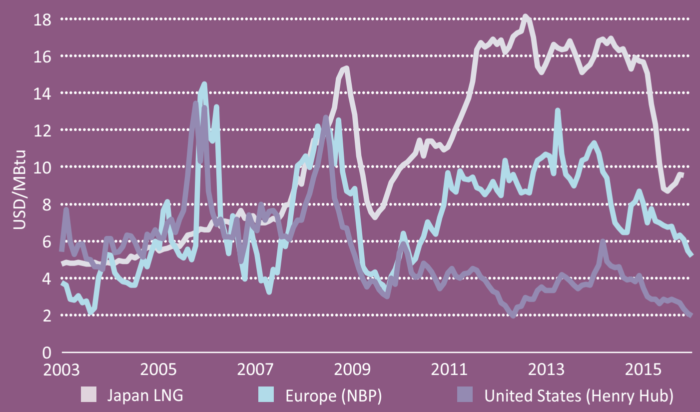
Tracking progress

An important medium-term role for natural gas in the 2DS is to facilitate the transition to low-carbon electricity generation. Given that the current growth rate of natural gas-fired power generation is down 0.4%, with its share in global power generation of 21.7%, natural gas-fired power has not been matching the strong growth in coal-fired generation.

Recommended actions

The competitiveness of natural gas relative to coal in daily electricity system operation is highly dependent on regional market conditions, in particular fuel prices. The introduction of carbon taxes and regulation of plant emissions could encourage coal-to-gas switching, while other electricity market mechanisms are required that recognise the potential benefits offered by natural gas-fired power, e.g. as a lower-carbon alternative to coal-fired generation and its operational flexibility to support the integration of variable renewables.

2.12 Natural gas spot prices



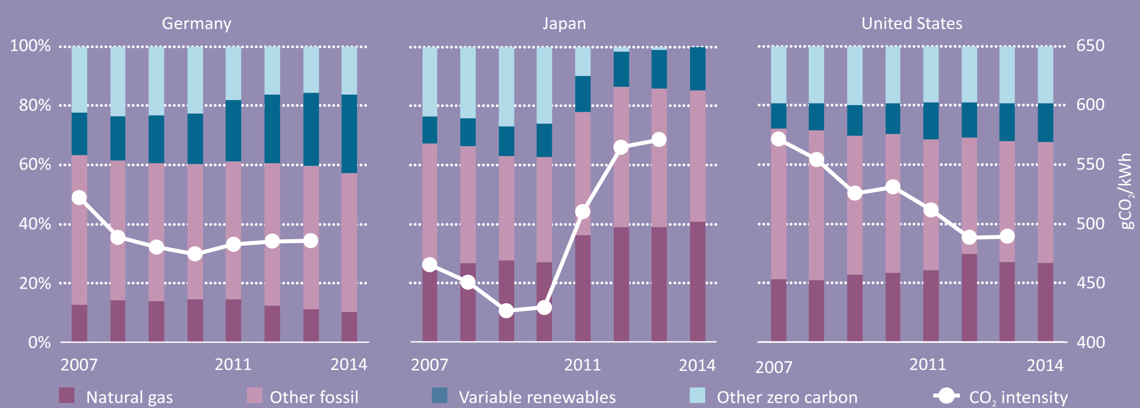
Recent developments

Persistent low gas prices in 2015 led gas generation to almost equal coal in the United States

Divergent trends in coal-to-gas switching are continuing in different regional markets

Sluggish electricity demand and increasing competitiveness of renewables eclipse gas-coal competition

2.13 Power generation mix and related CO_2 intensity



EU CO_2 PRICE

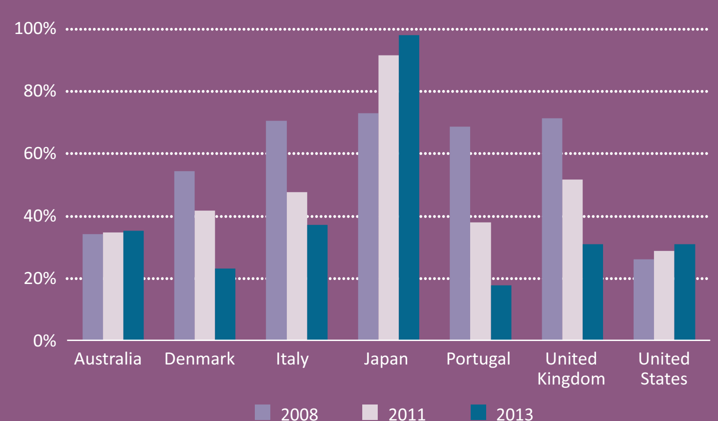
49 EUR/tCO_2

FOR SHORT-TERM COAL-TO-GAS GENERATION SWITCH

20 EUR/tCO_2

LONG-TERM CAPACITY INVESTMENT SWITCH

2.14 Natural gas-fired power capacity factors



For sources and notes see page 124

Coal-fired power

● Not on track

~ Limited developments

In 2013, global gross electricity production increased to 23 322 TWh, 41% of which was generated from coal-fired power plants. While total generation increased by 2.9%, the contribution from coal rose by 5%. In 2014, global coal consumption decreased from 7 991 million tonnes (Mt) to 7 920 Mt, declining for the first time this century.

Recent trends

In OECD countries, coal was responsible for 33% of the electricity generated in 2013, compared with 49% in non-OECD economies. Total coal-fired power generation in OECD countries continued to decline, with an estimated 3 435 TWh in 2014, down 2.1% from 3 508 TWh in 2013. This total was the lowest value for coal-based electricity generation in the OECD in the last decade. The decrease was driven mainly by developments in OECD Europe, where coal-based electricity generation fell by 68 TWh (-7.5%) in 2014 compared with 2013. The largest contributor to this decline was the United Kingdom, with a decrease of 34 TWh, corresponding to a year-on-year drop of 25%.

The United States has encountered a 20% decline in coal's share of power generation since 2000, due largely to weak electricity demand growth, low gas prices and competition from other fuels. Generation from coal rose by 69 TWh in 2013 and 3 TWh in 2014. On the other hand, Japan's coal-fired power generation has followed a stable growing trajectory, with its share increasing from 29.6% in 2012 to 32.4% in 2013, and to 33% in 2014.

In 2014, while China's electricity generation continued to increase, coal's share fell from 74% to 70% – down 203 TWh to 3 908 TWh. This decline marked the first decrease in coal-fired power generation in 40 years, largely as a result of an increase in electricity demand of just 3.8% in 2014, much lower than in the past. Circumstances contributing to this historic event were the combined effects of strong hydropower generation, new hydropower capacity additions, and increased generation from renewables and nuclear energy. China has set new standards for its coal power generation fleet, with programmes to continually improve performance and, importantly, an initiative that requires 28% of coal-fired generation to be combined heat and power (CHP) by 2020.

At the end of 2013, the capacity of coal-fired plants in OECD countries was 537 GW, down more than 82 GW compared with 2012. The United States made the greatest contribution, having retired around 6.8 GW in 2013, with a further 4 GW in 2014. In contrast, Japan increased its coal-fired capacity, adding more than 1.6 GW in 2013. Overall, Chinese coal-fired power capacity in 2013 increased by 35 GW to 792 GW, manifestly lower than the capacity increases in 2011 (+59 GW) and 2012 (+48 GW). In India as well, to meet the rapidly growing electricity demand, the installed capacity of coal-fired power plants rose from 158 GW in 2014 to 173 GW in 2015 (CEA, 2015), almost tripling since 2000.

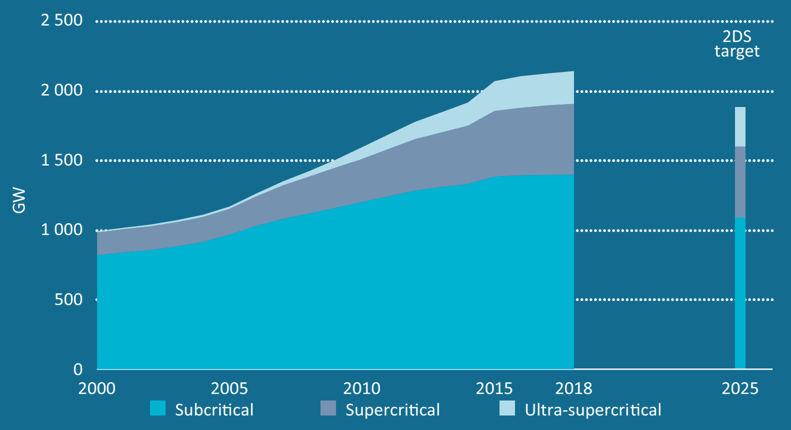
Tracking progress

The growth in global coal-fired generation between 2012 and 2013 was 455 TWh, with a capacity growth of 46 GW over the same period. These numbers suggest a slowdown from the growth rates of recent years. To meet the 2050 2DS targets, however, global emissions of CO_2 must plateau and then fall within the next five to ten years. While China is on target to meet this trajectory, coal-fired generation in India and the emerging economies of South-East Asia is projected to grow rapidly over the next decade or longer implying increases in CO_2 emissions.

Recommended actions

In general, though particularly in the emerging economies where coal-fired capacity is expanding, policy measures are required to ensure that processes are in place to assess the potential to deploy lower-carbon generation options, that generation from the less-efficient subcritical coal units is phased out and that new coal-fired units have efficiencies consistent with global best practice – currently supercritical or ultra-supercritical technologies. Where feasible, new coal-fired units should also be constructed carbon capture and storage (CCS) ready. Then, when policy or economics dictate, CCS should be deployed.

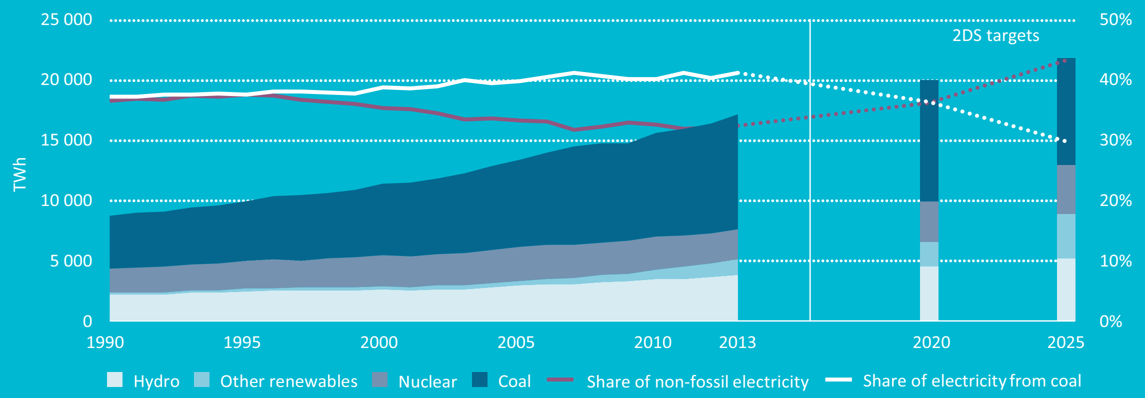
2.15 Coal capacity deployment



49%

OF ELECTRICITY GENERATED IN NON-OECD ECONOMIES IS FROM COAL-FIRED POWER PLANTS

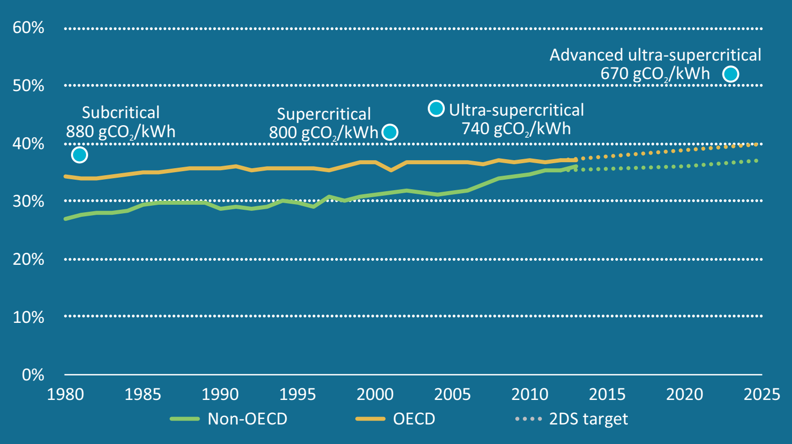
2.16 Coal and non-fossil power generation



70%

OF CHINA'S ELECTRICITY IS GENERATED FROM COAL

2.17 Average coal fleet efficiencies



For sources and notes see page 124

Carbon capture and storage

Not on track

Positive developments

In 2015, two new CCS projects began operating, including the Quest project with saline aquifer CO_2 storage; however, no investment decisions were taken on new projects. More investment from industry and support from government are needed to bring projects into the development pipeline to meet 2DS targets in 2025.

Recent trends

In 2015, two new large-scale CO_2 capture projects began operating. The Quest project in Canada's oil sands captures up to 1 million tonnes of CO_2 ($MtCO_2$) per year from hydrogen production at the Scotford Oil Sands Upgrader for storage at a depth of around 2 kilometres in an onshore saline aquifer. The Uthmaniyah project in the Eastern Province of Saudi Arabia will capture around 800 000 tonnes of CO_2 per year from the Hawiyah natural gas liquids recovery plant to be injected for enhanced oil recovery (EOR) at the Ghawar oil field. These two projects bring the total number of operating CO_2 capture projects globally to 15.

No positive investment decisions were taken on CCS projects, nor did any advanced planning begin in 2015, resulting in a fall in the total number of projects in the development pipeline. A constant flow of projects through development to operation is crucial to meeting the targets under the 2DS and for maintaining and growing the global technical capacity in CCS. Currently 17 projects are in development, with 7 under construction and 10 in advanced planning, down from a total of 24 in 2014.

A majority of CCS projects today supply or intend to supply CO_2 for EOR. Of the 32 CO_2 capture projects currently in advanced planning, construction or operation, 21 projects are providing CO_2 for EOR,[1] while 11 are storing or will store CO_2 in saline aquifers or depleted oil and gas fields.

A strong market for CCS does not yet exist in most regions globally. The implicit or explicit value of avoiding emissions in most areas is not yet sufficient to make CCS an attractive mitigation option in the absence of other support mechanisms. As economies look for deeper emissions cuts, CCS will become a more desirable mitigation option. As with other low-carbon technologies, the market for CCS projects in most regions will be created by policy and regulation; however, recently, a number of projects have been cancelled due to changes in policy and reductions in government financial support for CCS. One such notable change was the cancellation of the 1 billion British pound CCS competition in the United Kingdom in November 2015.

In a handful of regions, most notably in North America, the demand for CO_2 for use in EOR is creating a market for CO_2 capture. Over half of the CO_2 capture projects in development or operation globally are in North America, and all but one of these projects provides or intends to provide CO_2 for EOR.

Tracking progress

CCS is not on a trajectory to meet the 2DS target of 540 $MtCO_2$ being stored per year in 2025. At the end of 2015, the 15 large-scale operational projects have a total potential capture rate of 28 $MtCO_2$ per year, but only 7.5 million tonnes of the captured CO_2 is being stored with appropriate monitoring and verification. CCS needs to increase by an order of magnitude in the next decade to be on track to meet the 2DS in 2025.

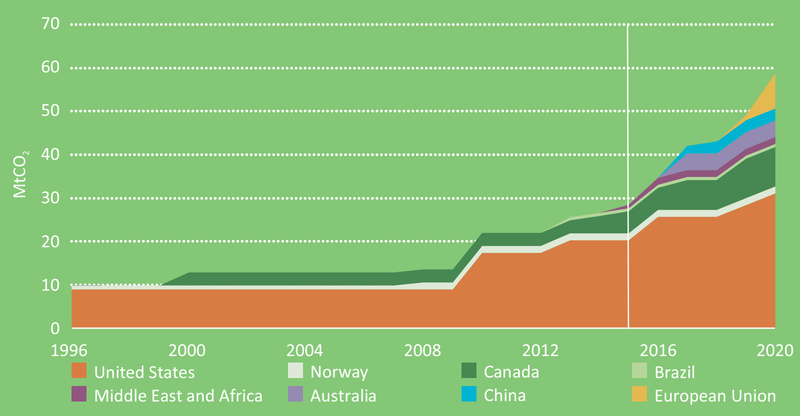
Recommended actions

Financial and policy support for CCS from governments is necessary to encourage projects into the development pipeline. At present, neither the cost of emitting CO_2 nor the level of government support is yet sufficient to make CCS an attractive emissions mitigation option in most contexts. Investment is needed now for CCS to be deployed in the next decade because projects typically take five to ten years from conception to operation.

Investment in storage resource development will de-risk projects and shorten the development time of projects. Storage characterisation and assessment are often the most time-consuming aspects of project development and outside the skill base of CO_2 capture project developers. Accessible developed storage resources will lower the costs and technical barriers for many potential CCS projects, particularly in industrial sectors.

1 CO_2 is retained and eventually stored through injection for EOR; however, additional monitoring and planning are needed to ensure the CO_2 is effectively stored. Refer to Technology overview notes page 124 for more information.

2.18 Large-scale CO_2 capture potential



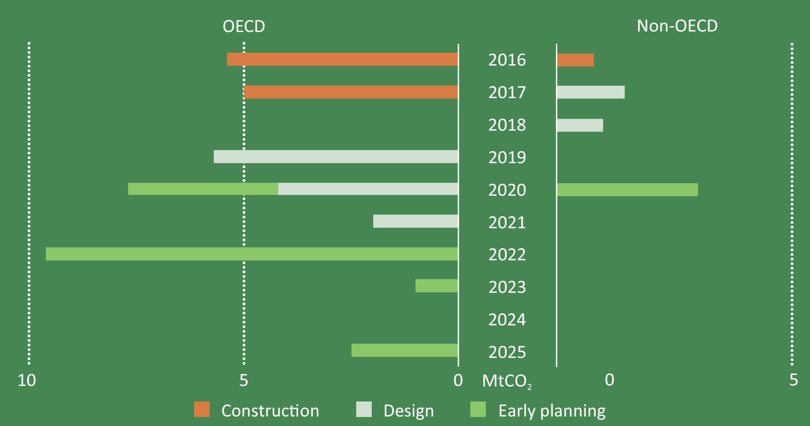
440

THOUSAND TONNES OF CO_2 CAPTURED IN THE FIRST YEAR OF OPERATION AT BOUNDARY DAM

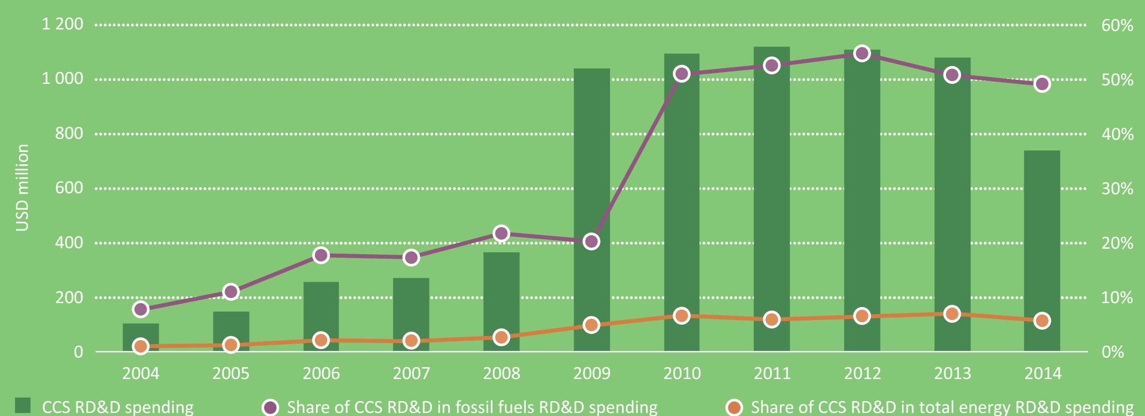
27%

OF CAPTURED CO_2 IS BEING STORED WITH MONITORING AND VERIFICATION TO ENSURE EFFECTIVENESS

2.19 Pipeline of capture capacity additions



2.20 IEA public RD&D spending



For sources and notes see page 124

Industry

Improvement needed
~ Limited developments

Industrial energy consumption grew to 152 exajoules (EJ) in 2013, 35% of the global total. Demand growth will put pressure on efforts to meet 2DS targets. Growth in CO_2 emissions must be reduced to 0.7% per year through 2025, while growth in energy demand must be limited to 2.0% annually, and innovative technologies quickly scaled up and deployed.

Recent trends

In 2013, energy consumption in industry[2] grew by 2.3%, with 62% of that growth occurring in China and India, where industrial final energy use jumped by 3.6%. Industrial energy use in OECD countries grew 3.3%, while Africa's growth was moderate at 1.2%, the Middle East declined by 1.9% and Latin America declined by 0.1%. No major changes in sectoral distribution of energy use occurred in 2013, with energy-intensive sectors[3] accounting for 68% of the industry total.

Despite an expected slowdown in demand for industrial products in China in coming years, non-OECD economies, led by India, have potential for strong demand growth. Some regions, such as China and Europe, are addressing overcapacity in key industrial sectors, particularly iron and steel and cement, to improve economic competitiveness, presenting both opportunities to improve efficiency and challenges for implementation of new technologies.

Policy makers throughout the world are increasingly considering cross-sectoral opportunities for energy efficiency and emissions reduction. A pilot programme in China encourages recycling, resource efficiency and life-cycle approaches to reduce the overall impacts of industrial products (SCC, 2013). The Perform Achieve and Trade (PAT) programme in India will be broadened in the second three-year cycle of the programme (Powermin, 2015). Public-private partnerships, such as SPIRE, FPInnovations and European Technology Platforms, incentivise the development of low-carbon industrial technologies and address barriers to adoption (IEA, 2015d).

Tracking progress

Globally, CO_2 emissions must be limited to 9.7 gigatonnes (Gt) of CO_2 in 2025, peaking by 2020, while industrial energy consumption growth must be limited to 2.0% annually, on average, through 2025 in the 2DS. The reduction in CO_2 emissions can be achieved, despite growth in energy consumption, through energy efficiency, best available technologies, switching to lower-carbon fuels, recycling and implementation of innovative process technologies in the long term. CCS will need to be introduced in industry as soon as 2020 and rapidly scaled up to capture 209 $MtCO_2$ by 2025.

Despite modest recent progress on technology demonstration and supportive policy frameworks, CCS in industry remains underdeveloped. In the context of volatile energy prices, energy savings-related investments will face challenges and require policy stability to minimise short-term uncertainty.

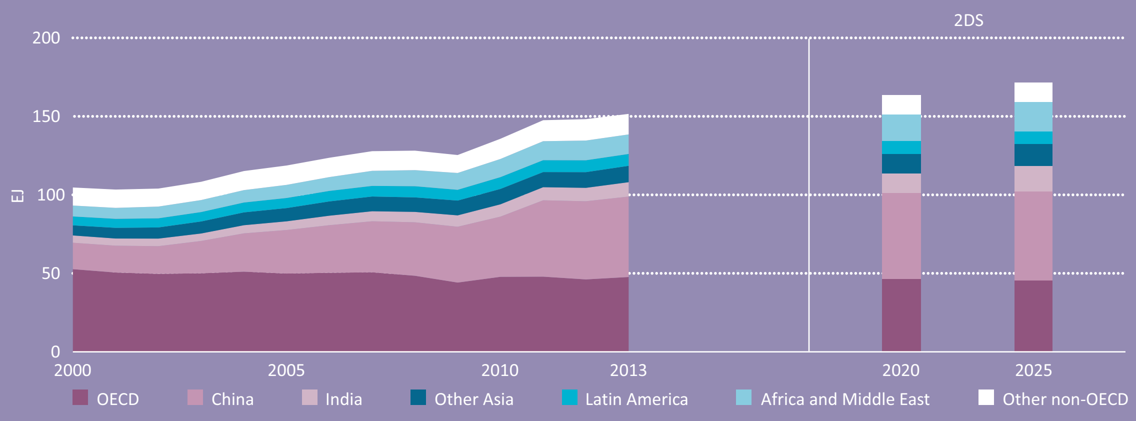
Recommended actions

Policy makers should continue to use traditional policy tools, such as fiscal benefits, energy performance standards for equipment, and promotion of energy management systems to support efficient technologies and practices. The impacts could be boosted by auditing installations and rewarding efficient performance. Improving the technological detail of industrial energy statistics would facilitate their implementation.

Industries should optimise use of locally available energy and material resources, by maximising process integration and efficiency, and by identifying nearby compatible uses for industrial by-products, such as excess heat. Governments should support these efforts through stable, long-term, low-carbon strategies, including tools such as legally binding emissions targets, carbon pricing or the removal of energy subsidies. Improving co-ordination between national and regional policies is also important, for example, by considering findings of heating and cooling mapping exercises in energy infrastructure planning. Public-private partnerships along product value chains should be encouraged as tools to identify and prioritise opportunities for energy and material efficiency. This type of collaboration can also unlock investment in research, development, demonstration and deployment for low-carbon processes that will become increasingly important in the long term.

2-3 Refer to Technology overview notes page 125 for notes associated with this section.

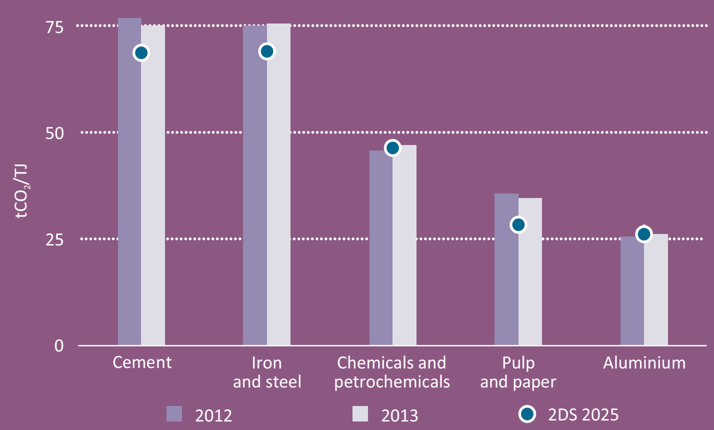
2.21 Global industrial energy use



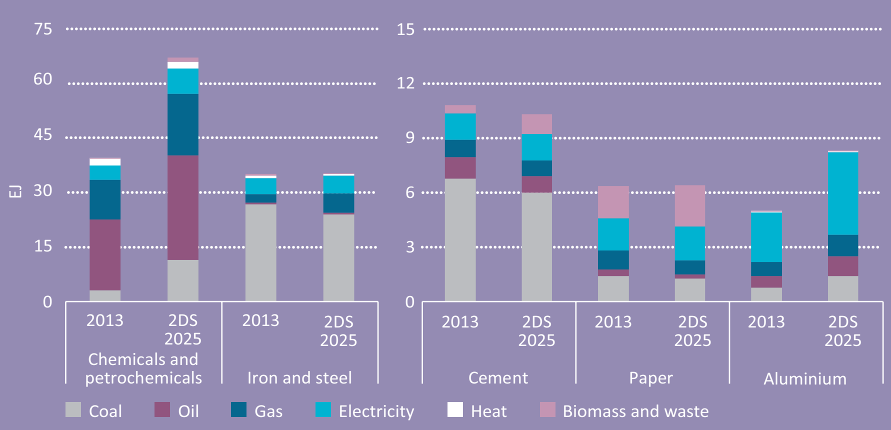
68%

OF INDUSTRIAL FINAL ENERGY IS USED IN FIVE ENERGY-INTENSIVE SUB-SECTORS

2.22 Direct energy-related CO_2 intensity



2.23 Industrial energy mix



Key point

CCS in industry will need to be introduced by 2020 and rapidly scaled up

For sources and notes see page 125

Aluminium

● Improvement needed
~ Limited developments

Incremental improvements in key processes have cut the energy intensity of primary aluminium production by 5.3% since 2000 (IAI, 2015a), but significant low-carbon technology developments will be needed to counteract continued increases in production. Recycled aluminium offers energy and emissions benefits, but is limited by scrap availability.

Recent trends

Primary aluminium production has grown significantly in the past few decades, by 110% from 24 Mt in 2000 to 51 Mt in 2013 (USGS, 2015, 2004). Secondary aluminium production, which requires up to 95% less final energy than primary production (IAI, 2009) before additional energy for scrap cleaning and alloy dilution is considered, is estimated to have grown by 88% to nearly 23 Mt.[4] Primary aluminium smelting is an electrolytic process, so electricity plays an important role. Fuels and feedstock in anode production and refining of bauxite into alumina are also required, and quality of bauxite influences the energy intensity of alumina refining. In recent years, energy intensities of aluminium smelting and alumina refining have decreased, while maintaining a share of secondary aluminium of over 30%,[5] even as total production increased dramatically. From 2000 to 2013, average primary smelting electricity intensity decreased by 5.3% and energy intensity of alumina refining by 8.7%.[6] At the same time, aluminium production growth contributed to an increase of 31% of energy consumption in the non-ferrous metals sector.[7] The trend towards diversified applications of aluminium in buildings, transport and consumer goods is expected to drive demand growth.

Global smelting energy intensity decreased by 0.5% in 2013. Chinese producers have overtaken most primary smelters to become the world's most efficient, at 13 740 kilowatt hours per tonne of aluminium (kWh/t Al).[8] China has also improved dramatically in alumina refining, with Bayer process intensity levels converging with other Asian and African refiners. However, non-Bayer process refining of low-quality feedstock is common in China, and raises the overall intensity level.[9] Latin America remains the least energy-intensive in alumina refining, at 8.8 GJ/t alumina in 2013. Regional energy intensity of secondary production is more difficult to track, because data are not publicly available. However, the increase in secondary production bodes well for aluminium production energy intensity.

Tracking progress

Growth in final energy use of no more than 3.6% a year on average to 2025 is required to meet the 2DS trajectory, while total aluminium production is expected to grow by 3.9% per year. Even greater reductions in CO_2 emissions are needed in the long term. Inert anode technology, if commercially demonstrated, could address the issue of process CO_2 emissions, which make up 37% of direct emissions in the aluminium sector, but will require significant deployment efforts in the long term.[10]

Co-ordinated efforts to deal with anode effects, non-CO_2 GHGs and outdated technology have reduced the sector's environmental impact. Nonetheless, several barriers remain to further improvement and to reaching the 2DS pathway. This sector's impact is highly correlated with CO_2 intensity of electricity generation. Low-quality bauxite, particularly in China, has given rise to alternatives to the Bayer process, which can be up to three times as energy-intensive (Rock, M. and M. Toman, 2015). The scope for shifting production to secondary routes is limited by scrap collection and availability. Most direct emissions reductions are incremental, as producers move towards point-feed prebake cells, decreased anode-cathode distance and optimised cathode design. Following a 2DS pathway requires more reliance on low-carbon innovative processes in the long term.

Recommended actions

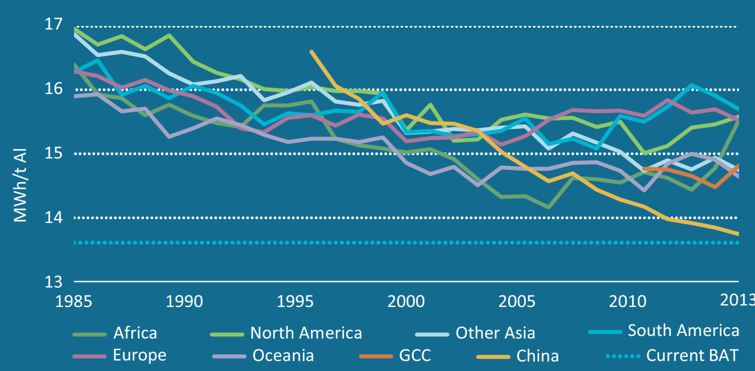
Aluminium sector stakeholders should collaborate with the public sector to develop and demonstrate innovative low-carbon technology options, such as inert anodes. Industry should collaborate with policy makers along the product value chain to push sectoral material and energy efficiency,[11] and consider life-cycle impacts and possible energy demand and carbon emissions reductions in other sectors (e.g. vehicle light-weighting). Major aluminium-producing countries should ensure their capacity is highly efficient, phasing out Søderberg smelters and using a modified Bayer process for refining low-quality bauxite.

4-11 Refer to Technology overview notes page 125 for notes associated with this section.

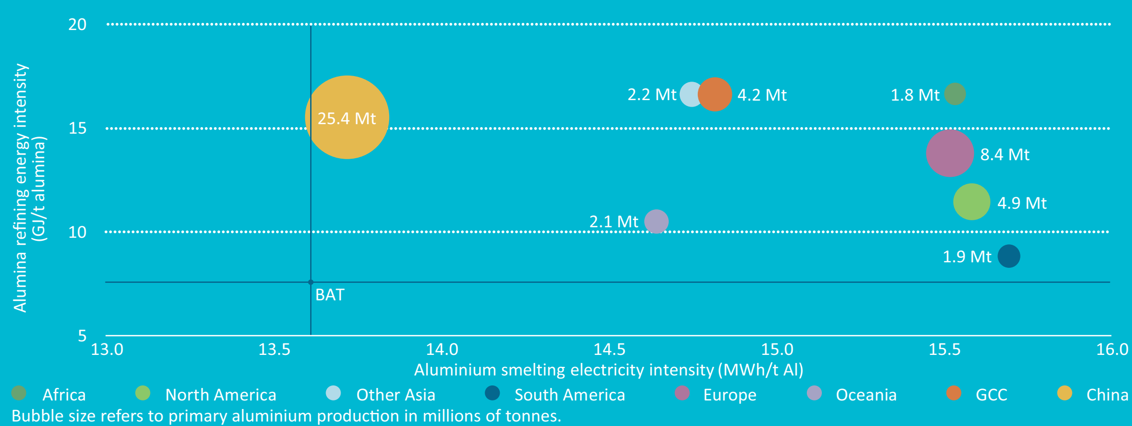
32%

SHARE OF SECONDARY PRODUCTION IN 2025 BUT DEEPER CO_2 CUTS ARE NEEDED[12]

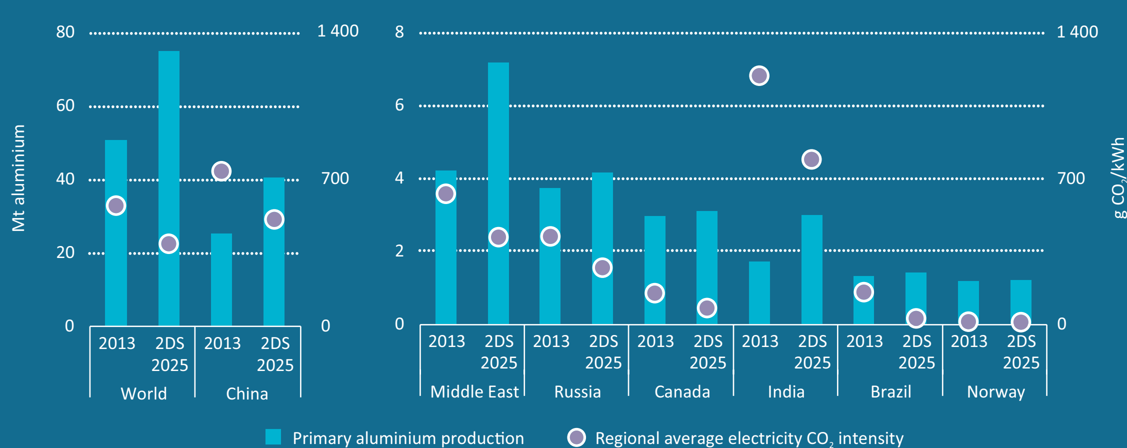
2.24 Electricity intensity of smelting



2.25 Alumina refining and aluminium smelting energy intensities



2.26 Primary aluminium production and average electricity CO_2 intensity



For sources and notes see page 125

Transport

● Improvement needed
~ Limited developments

Transport sector GHG emissions account for 23% of global energy-related GHG emissions, and have grown at a rate of 1.9% per year over the last decade. Continued dependence on oil means that nearly all growth in transport energy use translates directly into higher GHG emissions. Decisive near-term actions are required to bring transport emissions onto a trajectory consistent with 2DS.

Recent trends

Transport is the least diversified energy demand sector. The portfolio of energy supply sources has not noticeably changed in more than three decades. Prior to the 1973 oil crisis, 94% of transport total final energy consumption (TFC) came from petroleum products. In 2015, more than 93% of TFC was still sourced from petroleum-based fuels. Biofuels and natural gas have made some inroads; biofuels now provide 2.5% of TFC in transport, and natural gas provides 2.8%. In certain markets that provide a strong and consistent portfolio of fiscal and regulatory policies, electric vehicles are beginning to offer a viable alternative to conventional internal combustion engine (ICE) road vehicles.

Most of the growth in transport energy over the past 15 years is attributable to non-OECD economies, accounting for 86% of the global increase in passenger activity, 73% of the growth in freight activity, 91% of the increase in energy use, and 94% of the increase in GHG emissions. Rising standards of living over the coming 15 years across the developing world are likely to spur growing demand for mobility services and freight movement.

Between 2000 and 2015, despite sizeable increases in global activity – passenger activity (in passenger-kilometres) grew by 87%, and freight activity (in tonne-kilometres) grew by 68% – energy use and emissions increased by only about 38% (2.15% per year). The difference between activity growth on the one hand and energy use and emissions on the other is explained by technological and operational improvements in vehicle efficiency and by modal shifts.

Disparate levels of access to modern mobility are reflected by the wide regional discrepancies in transport energy use per capita (which vary across regions by more than an order of magnitude) and in aggregate. Greater energy use is not necessarily coupled with superior mobility, because it can also indicate inefficiencies in providing adequate access to mobility and goods.

Tracking progress

Transport energy demand has increased at an annual rate of just under 2.0% over the last decade. The fact that emissions increased more slowly than they did in the first decade of this century, when they grew at an annual rate of 2.15%, can be attributed primarily to efficiency improvements, above all in the passenger light-duty vehicle (PLDV) fleet, which further shows that transport emissions can be brought under control.

To meet 2DS targets, energy demand must stabilise, and GHG emissions need to peak and begin to decline within the coming decade. Negligible progress has been made in weaning transport off its dependence on oil. Moreover, gains in PLDV efficiency have been undermined to some extent by a growing gap between tested and real-world fuel economy.

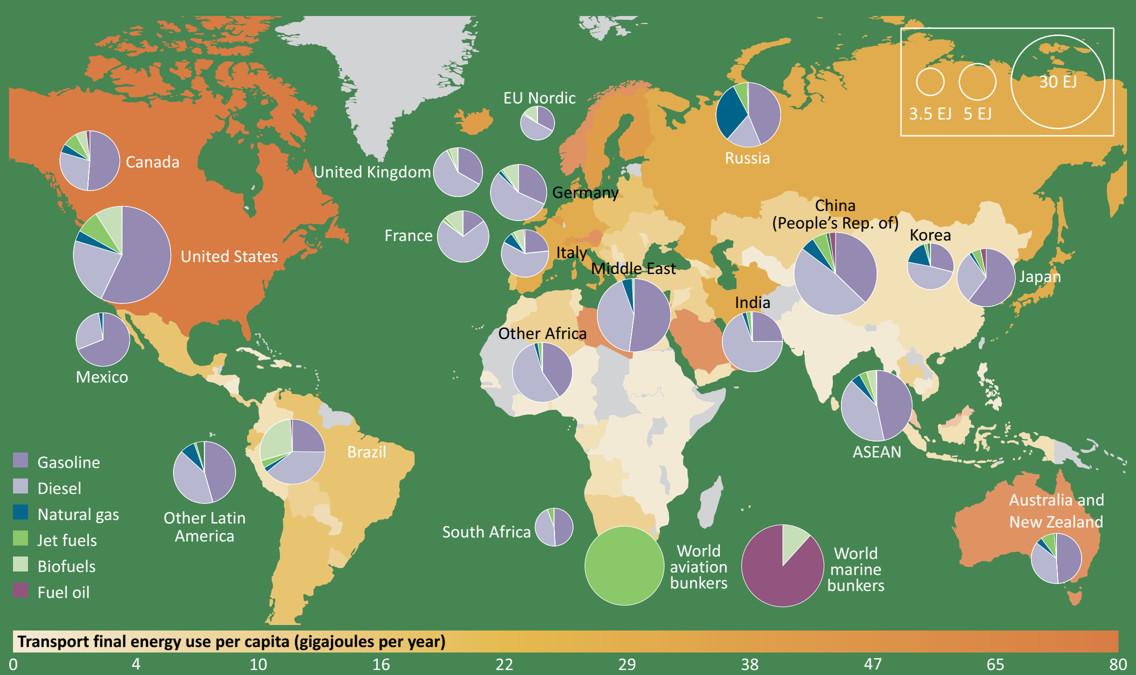
Recommended actions

Transport policies must raise the costs of owning and operating the highest GHG emissions-intensity modes, especially in the current context of low oil prices. Fuel subsidies must be phased out and alternative fuel taxes based on well-to-wheel[13] GHG emissions established in their stead. Vehicle taxes must also be levied. Ideally, these taxes should be tiered according to vehicle energy- or emissions-intensity performance (i.e. as "feebates"). Feebates can be revenue-neutral, but are more effective in curbing transport energy demand if they are applied so as to increase net governmental revenues, which can then go to other transport efficiency investments (e.g. low-carbon fuel research, development and demonstration [RD&D], public transport). Fiscal policies must be supplemented by other national and local measures. Regions that do not currently enforce fuel economy and tailpipe emissions regulations of light-duty vehicles and freight trucks should set up such frameworks.

13 Refer to Technology overview notes page 127 for notes associated with this section.

2.27 Developments in passenger and freight transport

2.28 Transport energy use, total and per capita, 2013



For sources and notes see page 127

Electric vehicles

On track

Positive developments

The threshold of 1 million electric cars[14] on the road was crossed in 2015. Annual electric car sales grew by 70% over 2014, catching up to rates needed to meet the 2DS target. Nevertheless, even in a context of rapidly decreasing battery costs, ramping up from 1.15 million electric cars today to 20 million by 2020 remains a very ambitious challenge that will not be met without sustained government support.

Recent trends

With a growing selection of models on the market, 477 000 electric passenger cars were sold in 2015, of which 51% were BEVs. The main markets were China – which became the world's largest electric car market in 2015 – the United States, the Netherlands and Norway. Together, these countries accounted for 70% of electric cars sold worldwide. Electric cars are gaining a foothold in a growing number of national markets; the number of countries with a market share of electric cars greater than 1% has grown from three in 2014 to six in 2015.

The provision of public charging infrastructure continued to accelerate, with the number of alternating current (AC) "slow" chargers growing from 94 000 in 2014 to 148 000 by the end of 2015. Installation of direct current (DC) "fast" chargers grew fastest – 4.5 times in China alone – and with a global network estimated at 57 000 chargers by the end of 2015. The build-out of fast chargers, many of which are publicly accessible, in parallel with steady progress towards extending the driving range of electric vehicles (EVs) may narrow the gap between EVs and conventional ICE performance, fostering broader EV adoption.

Electric 2-wheelers far outnumber electric cars, with more than 200 million units operating in China alone. Electric buses, which can make major contributions to reducing pollution in urban areas, have been widely deployed in China, growing from 29 500 vehicles in 2014 to more than 170 000 in 2015. For other vehicle types (e.g. light commercial vehicles, freight trucks and other specialised operations) data are scarce; sales have yet to take off as they have in electric passenger vehicles. A few initiatives may, however, indicate an emerging niche for electrification. Manufacturer BYD is expanding its focus beyond electric cars and buses to construction vehicles, seaport and airport operations vehicles, and other specialised niche markets (Hanley, S., 2015). La Poste, the national mail carrier in France, has electrified its delivery fleet with 5 000 fully electric Renault Kangoos and plans to double its electric fleet by 2020 (Renault, 2015). In a city such as Paris, where buses and trucks are responsible for more than half of the mono-nitrogen oxide emissions from transport (Airparif, 2012), electrifying urban bus and truck fleets can deliver cost-effective GHG and local pollutant reductions.

Tracking progress

Electric car sales grew by 70% in 2015, a positive development after a slowdown in annual sales growth (53%) in 2014. Remaining on track with the 2DS will require sustained annual average sales growth (from 66% through 2020 to 39% through 2025). This ambitious near-term objective seems achievable with sustained policy and funding support for technology improvements, consumer purchase and use incentives, and infrastructure deployment.

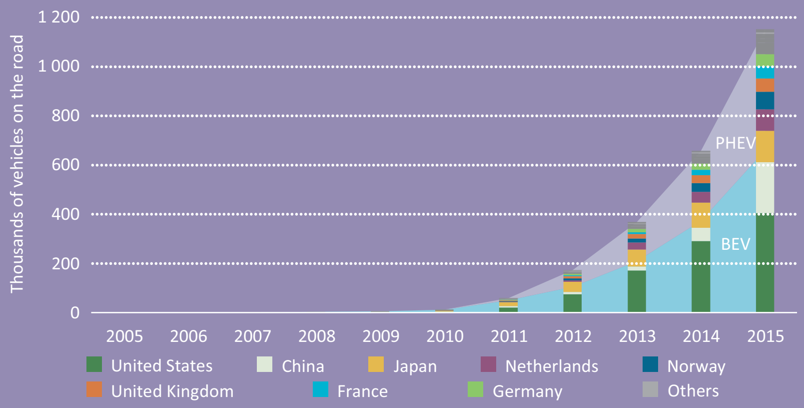
Recommended actions

Continued support for RD&D is needed to hasten the milestone year when purchase costs of cars with all-electric ranges capable of meeting most driving needs reach parity with ICE cars. In addition to funding basic and applied technical research, governments must also prioritise comparative policy analysis and market research focusing on consumer preferences to enable electric cars to bridge the proverbial chasm to the mainstream market.

Public policy can also play a powerful role in aligning private and social costs of vehicles. Differentiated vehicle taxation, based on environmental performance, can be used to bring purchase prices faced by car consumers closer to parity with ICE vehicles, and can be designed to be revenue-neutral (or even as net revenue sources), hence increasing their fiscal durability. The vehicle taxation structure played a key role in the successful EV deployment that is taking place in Norway and the Netherlands.

14 Including plug-in hybrid (PHEVs) and battery electric (BEVs) cars.

2.29 Global electric car stock



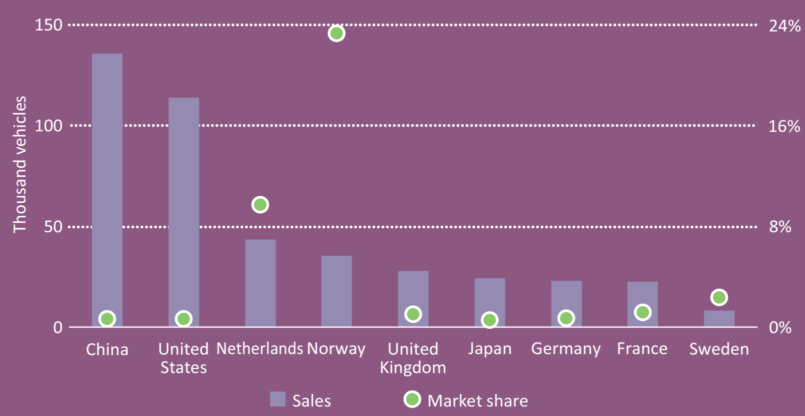
3%

APPROXIMATE SHARE OF EVS IN NORWAY'S PASSENGER CAR STOCK

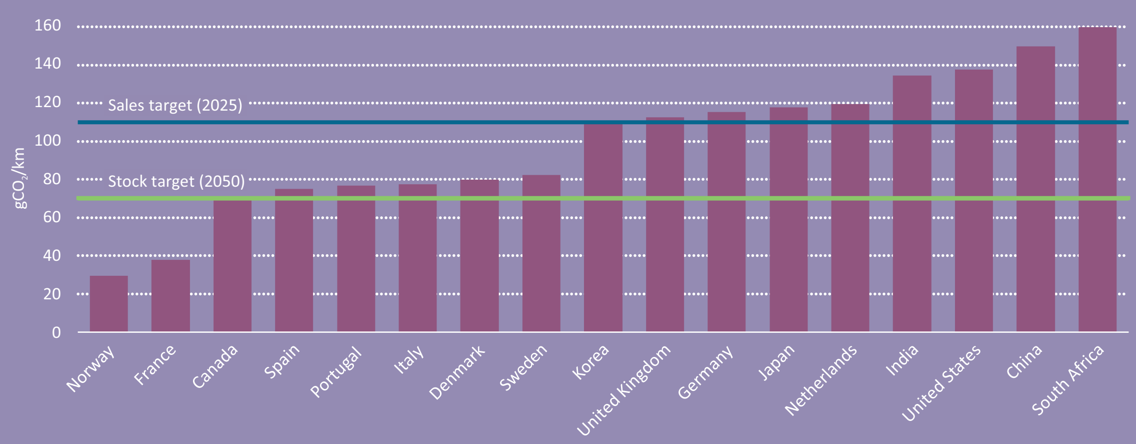
Key point

Decarbonisation of electricity must accompany the push to electrify transport in the 2DS

2.30 Plug-in electric car sales, 2015



2.31 Well-to-wheel GHG emissions intensity of new electric cars, 2015



For sources and notes see page 127

Aviation

Improvement needed

~ Limited developments

With a historical annual increase in passenger-kilometres of 5.3% since 2000, aviation is the transport mode projected to grow the most in the coming years, especially in non-OECD economies. In 2013, global aviation energy demand reached 11.1 EJ.[15] Associated CO_2 emissions due to fuel combustion accounted for 2.6% of the global total in the same year.

Recent trends

Aviation is the transport mode that experienced the greatest activity increase in the past decade, having reached total transport activity of 5.8 trillion passenger-kilometers in 2013.[16] OECD countries accounted for 59% of the total revenue passenger-kilometres in 2013 (down from 70% in 2005). Shares of energy demand and CO_2 emissions in both OECD countries and non-OECD economies closely track passenger-kilometre shares.

China, the Association of Southeast Asian Nations (ASEAN), and the Middle East experienced the largest increases in passenger-kilometres since 2000. Growth in the Middle East was augmented by increasing reliance on its large-capacity airports as connection points between the eastern and western hemispheres. China is expected to improve its aviation infrastructure by constructing 100 new airports by 2020 (JADC, 2014) to support growing domestic and international demand.

IEA data on energy consumption and International Civil Aviation Organization (ICAO) passenger-kilometre data show that the historical energy intensity, expressed in energy units per passenger-kilometre, declined by an average 3.9% per year, globally, from 2000 to 2013 (ICAO, 2013; IEA, 2015g). This exceeds the goal set in 2008 by the Air Transport Action Group (ATAG),[17] which committed to improve the fleet fuel efficiency by 1.5% per year through 2020 (UN, 2014). This also exceeds the goal set by ICAO in 2010 (reaffirmed in 2013) to improve fuel efficiency by 2% per year through 2020 (UN, 2014).

The average energy efficiency per passenger-kilometre of new aircraft improved more rapidly in the 1980s and thereafter continued to improve, though at a slower rate, after 1990. This seems to indicate that meeting fuel efficiency goals for 2020 will likely become more difficult over time (Kharina and Rutherford, 2015). Slackening efficiency improvements for new aircraft deliveries call for an increased focus on deploying technology that leads to fuel savings (e.g. lower empty weights per unit of pressurised floor area). Encouraging signs come from the recent work of airplane manufactures on efficient aircraft, such as the upcoming Airbus 320neo and the Boeing 737MAX (Kharina and Rutherford, 2015). Other positive developments include increasing load factors, partially achieved through technical advances accommodating higher seat density (Airbus, 2014) and through air traffic improvements (Boeing, 2014).

Aircraft manufacturers have begun demonstrating the feasibility of using biofuels for aviation and supporting biofuel development activities; one example of this trend is Boeing (2015). Industry initiatives, such as the European Biofuel FlightPath Initiative, aims to produce 2 Mt of aviation fuel from renewable sources per year by 2020.

Tracking progress

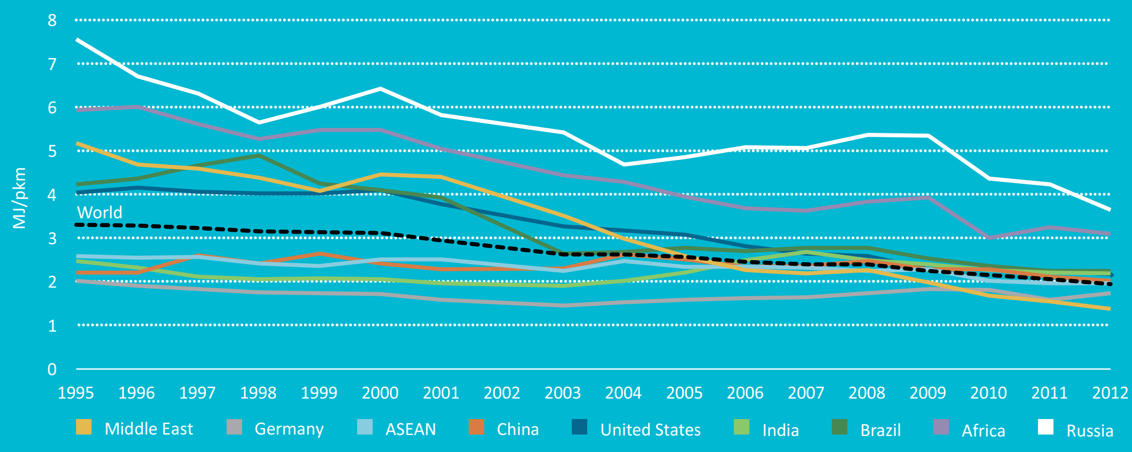
While recent annual average fuel efficiency improvements of 3.9% have exceeded aviation industry targets, meeting the aspirational global fuel efficiency improvement beyond 2020 of 2% per year to 2050 (ICAO, 2013) will become increasingly challenging, suggesting a serious risk of not meeting 2DS targets.

Recommended actions

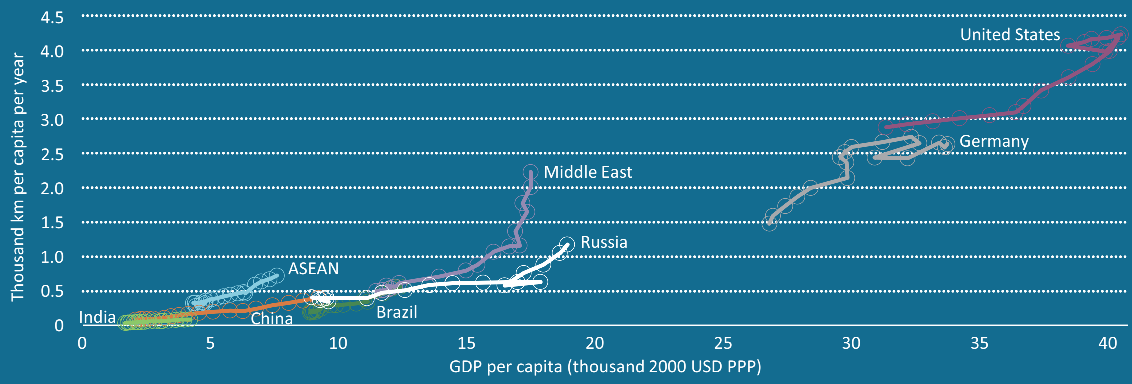
IEA analysis suggests that CO_2 taxes or other market-based policies will be needed to promote fuel efficiency improvements exceeding the 2% annual improvement set by the ICAO goal until 2050. The introduction of CO_2 taxes on aviation fuels and mobilisation of investments for the development of high-speed rail networks would contain activity growth. By incentivising aviation companies to reduce expenditures on fuel, carbon taxes also monetise energy efficiency improvements. Even accounting for significant shifts to high-speed rail and accelerated efficiency improvements, a 55% biofuel share in 2050 is necessary to achieve the carbon-neutral growth and the ATAG CO_2 emissions reduction targets.

15-17 Refer to Technology overview notes page 127 for notes associated with this section.

2.32 Energy intensity in aviation



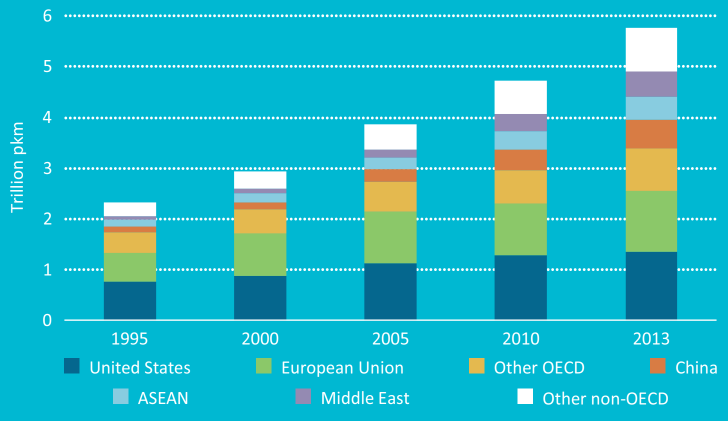
2.33 Aviation demand and GDP per capita, 1995-2013



50%

IATA target for CO_2 emissions reduction from 2005 levels by 2050. Airlines have responded by investing in biofuels production and signing long-term fuel off-take agreements. IATA also recommends the introduction of a global carbon offset programme.

2.34 Aviation demand by region



For sources and notes see page 127

Biofuels

● Not on track
↗ Positive developments

Despite a low oil price environment, global biofuels production increased to around 134 billion litres (L) (3.2 EJ) in 2015. However, while conventional biofuels are on course to meet 2DS targets for 2025, significantly accelerated commercialisation of advanced biofuels is necessary to fully achieve 2DS requirements for decarbonisation of the transport sector.

Recent trends

In 2015, conventional biofuels provided around 4% of world road transport fuel. Double-digit global production growth observed pre-2010 has slowed to a modest 2%[18] due to a combination of structural challenges and policy uncertainty in key markets. The increasing efficiency of the vehicle fleet in the United States, compounded by a low market penetration of flexible-fuel vehicles and absence of widespread fuel distribution infrastructure for high biofuel blends, has dampened growth. Brazilian ethanol consumption increased strongly in 2015, but the fragile economic state of the sugar cane industry means investment in ethanol production capacity is well below previous levels. Conversely, production is expanding to new areas, with promising new markets developing in the non-OECD Asia and non-OECD Americas regions.

Biofuels mandates, strengthened recently in several key markets, including Brazil and Indonesia, have effectively shielded biofuels demand from a low-oil-price environment that reduced prices for gasoline and diesel. These lower prices provided a window for countries such as India and Indonesia to remove fossil fuel subsidies.

After a prolonged assessment of land-use change sustainability considerations, the European Commission introduced a 7 percentage point (pp) cap on the contribution of conventional biofuels towards the European Union 2020 target of 10% renewable energy in transport. This revision, which also incorporates a 0.5 pp non-binding advanced biofuels sub-target, creates an opportunity for advanced biofuels to provide a larger contribution to meeting the remainder of the target.

A notable scale-up in the advanced biofuels sector has occurred, with seven new commercial-scale advanced biofuel plants using biomass wastes and agricultural residue feedstocks commissioned over 2014-15, bringing the total number of facilities to ten. The ability of these plants to demonstrate the economic and technical feasibility of commercial-scale production will shape future deployment prospects.

Tracking progress

Global production of conventional biofuels is on track to meet 2DS requirements. The visible advanced biofuels project pipeline could deliver production of around 2.8 billion L (0.06 EJ) in 2020 from a current low base. However, this production level would remain 14.7 billion L (0.4 EJ) short of 2020 2DS needs, and leaves a twentyfold scale-up in production volumes necessary between 2020 and 2025 to achieve the required 56.8 billion L (1.5 EJ) contribution of advanced biofuels to the 2DS in 2025.

Recommended actions

Stable and long-term policy frameworks can facilitate expansion of the advanced biofuels sector and enable investment and production cost reduction potential, providing a more favourable investment climate. National transport sector targets for emissions reduction, shares of renewable energy or, as in Sweden, phasing out fossil fuels provide a framework for biofuels markets to prosper. These targets can also include sub-targets for the harder-to-decarbonise road freight, marine and aviation sectors. Alternatively, legislation to stipulate defined reductions in the life-cycle carbon intensity of transportation fuels (e.g. as established in California) should ensure demand for biofuels with the highest emissions reduction potential.

Widespread advanced biofuels mandates will also be essential to accelerating uptake. These mandates can be complemented by the provision of financial de-risking measures to support expansion while initial investment costs remain high, tax incentives and financial mechanisms to support advanced biofuel technological innovation and commercialisation.

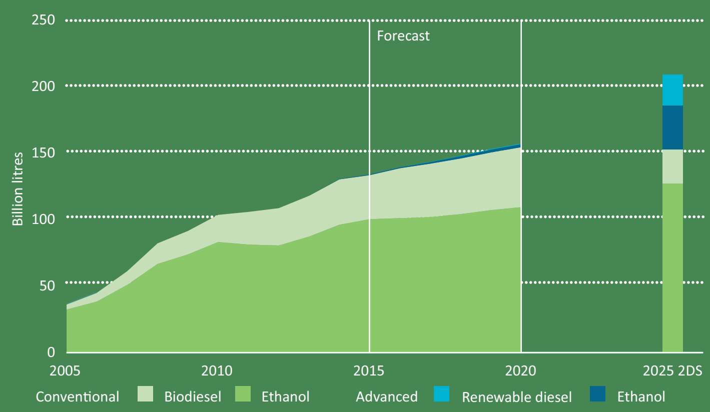
The expansion of the biofuels market must respect environmental, social and economic sustainability considerations via industry benchmarking against recognised sustainability indicators, such as those developed by the Global Bioenergy Partnership, and strong governance frameworks – for example those in place for the European Union sustainability criteria for biofuels.

18 Annual growth rate 2014-15 from IEA analysis. Refer to Technology overview notes page 128 for more information.

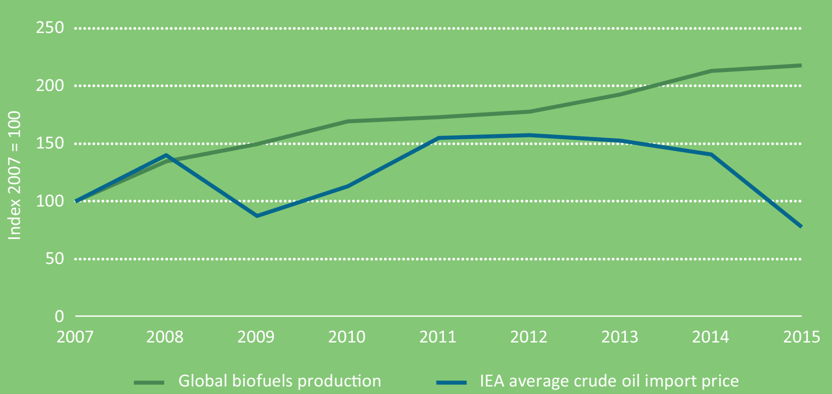
7

COMMERCIAL-SCALE ADVANCED BIOFUEL PLANTS COMMISSIONED IN 2014-15, ADDING OVER 650 MILLION LITRES OF NEW PRODUCTION CAPACITY

2.35 Global biofuels production



2.36 Biofuels production and crude oil price



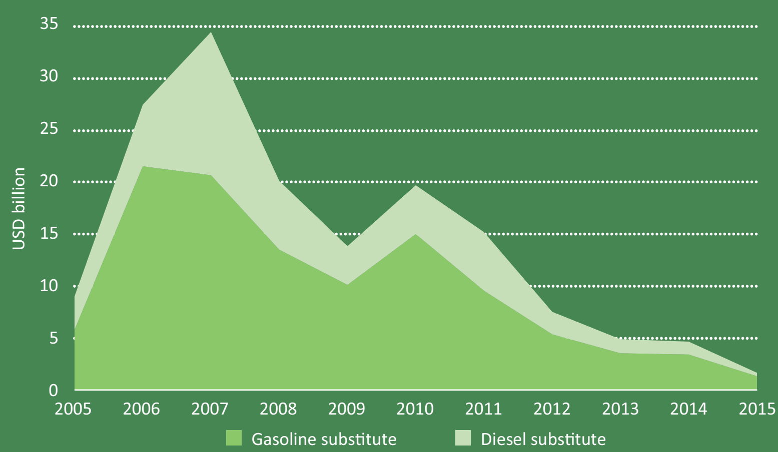
Key point

Mandates ensure biofuel demand during periods of low oil prices, allowing production to reach 4% of road transport fuel in 2015

95%

OF NEW REGISTRATIONS IN BRAZIL IN 2015 WERE FOR FLEXIBLE-FUEL VEHICLES

2.37 Global biofuels industry investment



For sources and notes see page 128

Buildings

Not on track

Positive developments

Buildings sector energy intensity per square metre has improved in many regions, but not fast enough to offset the doubling of global floor area since 1990. Large energy efficiency potential remains untapped, and assertive action is needed now to speed up intensity improvements by at least 50% and avoid the lock-in of inefficient, long-lived investments to 2050.

Recent trends

The global buildings sector consumed more than 120 EJ in 2013, or over 30% of total final energy consumption. Direct coal consumption in buildings decreased significantly since 1990, while oil use remained flat. At the same time, natural gas use in buildings grew by 40%, meaning that total fossil fuel consumption grew by roughly 8%. Building electricity consumption has more than doubled since 1990, and buildings accounted for half of global electricity demand in 2013. When upstream power generation is taken into account, the buildings sector represents almost one-third of global CO_2 emissions.

A concerted global effort towards energy efficiency in buildings is crucial to offset building energy demand growth while still providing comfort and improved quality of life. The energy efficiency potential in the buildings sector is substantial: globally, the deployment of best available technology and energy efficiency policies could yield annual energy savings in buildings of more than 50 EJ by 2050 – equivalent to the combined energy use of buildings in China, France, Germany, the Russian Federation (hereafter "Russia"), the United Kingdom and the United States in 2012.

Global building energy performance (as measured by final energy consumption per floor area) improved by 1.5% per year over the last two and a half decades as the result of the development and enforcement of building energy codes and energy efficiency policies in many countries. Yet progress has not been fast enough to offset growth in building floor area and ownership of energy-consuming equipment. To date, very few countries have decoupled building energy consumption from population growth, and energy consumption per capita is still growing in most regions (IEA-IPEEC, 2015).

Noteworthy in 2015 was the announcement at COP21 in Paris of a new Global Building Alliance for Buildings and Construction on how to transform the buildings sector in support of a low-carbon economy. The Global Environment Facility, World Resources Institute and United Nations Environment Programme also announced the Buildings Efficiency Accelerator (BEA), with new funding to catalyse increased uptake of energy efficiency in buildings in developing countries.

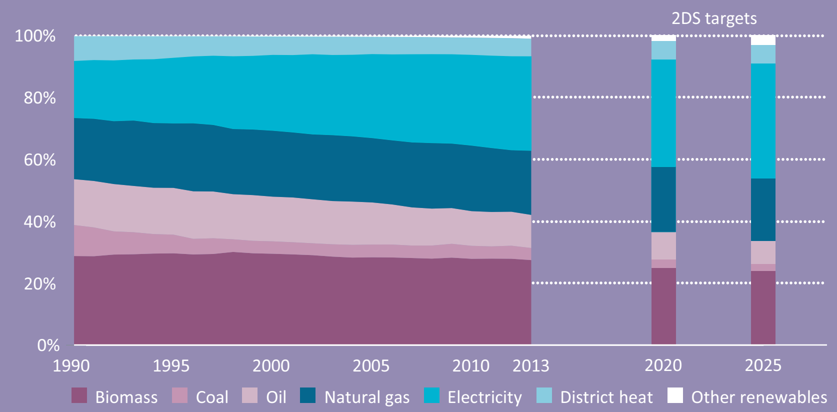
Tracking progress

Current investment in building energy efficiency is not on track to achieve the 2DS targets, or below 2°C as set out by COP21. While an increasing number of countries have implemented or improved energy efficiency policies related to building construction and equipment, progress has not offset increasing demand for thermal comfort and ownership of energy-consuming products. The adoption and implementation of energy efficiency need to be accelerated rapidly, especially in emerging economies, such as China and India, where a window of opportunity still exists to address future building energy demand and prevent the lock-in of inefficient, long-lived building investments. In developed countries, acceleration of deep energy renovations of existing buildings and installation of high-efficiency building products are critical to reaching 2DS targets (or below). Globally, building energy performance needs to improve from a rate of 1.5% per year from the past decade to at least 2.5% per year over the next decade to 2025.

Recommended actions

Governments need to develop and improve building energy codes and performance criteria for both new and existing buildings. Educational programmes, capacity building and improved building energy data resolution should be used to help inform and improve policy design, adoption and enforcement. Effective policies and financial incentives are needed to leverage aggressive energy efficiency action in buildings to establish market demand. These efforts are crucial in the short term because 2DS objectives will be more difficult to achieve if energy efficiency action is not taken in the coming decade given the long life of many building investments.

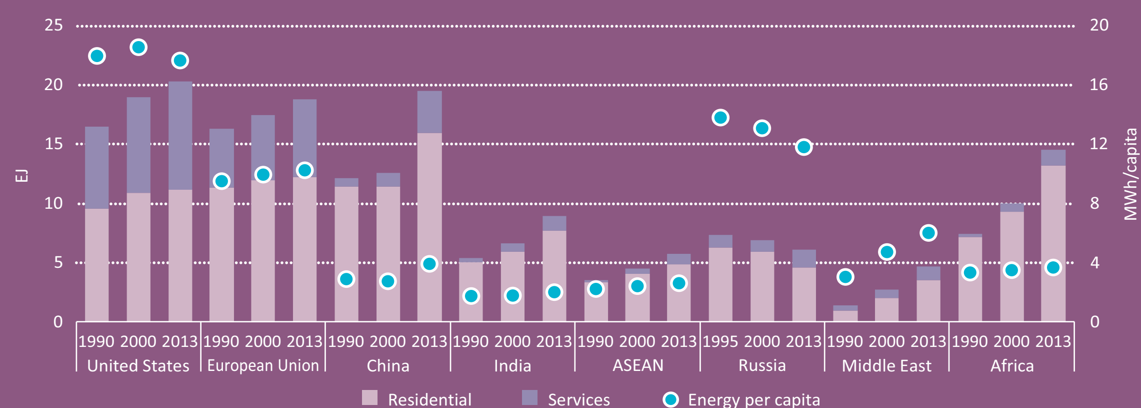
2.38 Buildings energy use by fuel



5%

DECREASE IN ENERGY PER PERSON IN THE UNITED STATES IN 2000-13 BUT INCREASES IN MOST COUNTRIES

2.39 Total and per-capita energy use in buildings



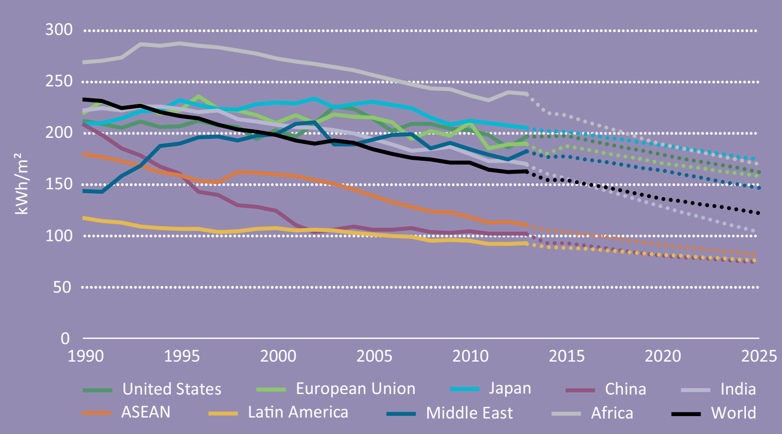
IMPROVEMENT RATE OF BUILDING ENERGY PERFORMANCE NEEDS TO GO FROM

1.5%

PER YEAR TO AT LEAST

2.5%

2.40 Energy use per square metre



For sources and notes see page 128

Building envelopes and equipment

● Not on track
↗ Positive developments

Continued adoption and enforcement of building energy codes and energy-efficient equipment have improved heating and cooling intensities since 1990. Yet investments have not kept pace with buildings sector growth and demand for greater comfort, especially in emerging economies. Deep energy renovations of existing buildings are not happening fast enough to meet 2DS targets.

Recent trends

Heating and cooling needs in buildings, including water heating, account for an estimated 55% of global building energy loads. Space heating continues to be the largest end use, accounting for roughly 35% of global building energy use in 2013, while space cooling is the fastest-growing end use, having increased by more than 4% per year since 1990. Progress has been made on improving the performance of equipment and building envelopes, which have the most influence over heating and cooling needs. However, energy intensity improvements (roughly 2% per year globally) have not been fast enough to offset growth in total building floor area (roughly 3% per year) and demand for greater comfort.

Advancement of deep energy renovations in the world's existing building stock is slow. Globally, improvements are far from the 2% to 3% annual deep energy renovation rates needed to meet 2DS targets. Some notable progress has been made in countries with strong building retrofit incentives, such as Germany and France, where 15 billion to 20 billion United States dollars have been spent in recent years on building energy efficiency, including renovating existing buildings (Robert, A., 2015; KfW, 2015). Typical building energy efficiency improvements in the 10% to 20% range are insufficient, locking in investments below the cost-effective potential.

Progress in new buildings through developing and improving enforceable mandatory building energy codes is slow, especially in rapidly emerging economies where efficiency improvements are not keeping pace with buildings sector growth. Notable progress includes recent state-level adoption of improved building codes in India, with 23 of the 36 Indian states and territories either having adopted or currently in the process of adopting the Energy Conservation Building Code. By contrast, a large number of countries still have voluntary or no building energy codes, while many markets still have weak enforcement infrastructure, limiting the effectiveness of mandatory codes.

Continued adoption of efficient space heating, cooling and water heating equipment is promising, with many countries having enacted mandatory or minimum energy performance standards (MEPS). However, equipment standards and average product efficiencies are still far below best available technology in many markets. A stronger push is needed to ensure the installation of high-efficiency equipment and to minimise the difference between MEPS and best-in-class equipment efficiency.

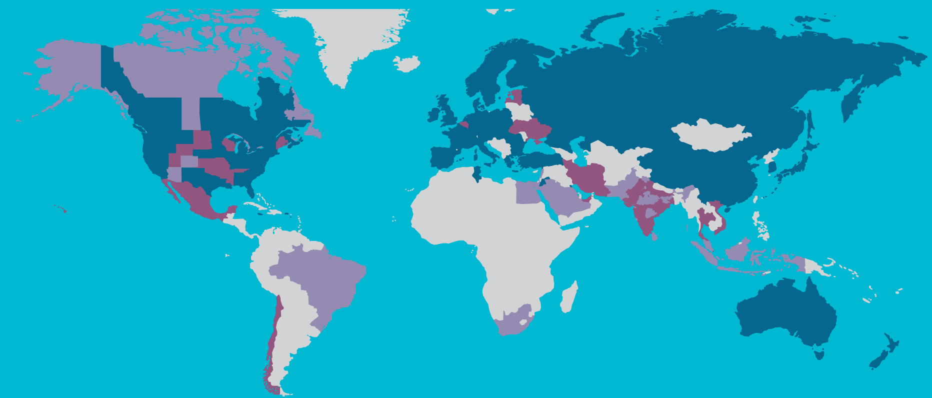
Tracking progress

Despite some progress on deep energy renovations in existing buildings, the current rate is not on track to achieve the recommended 2% to 3% annual building renovation level. Industry- and government-funded research and development (R&D) programmes have continued to enable demonstration and deployment of advanced building envelope and equipment technologies. These efforts have included advancements in super-insulating materials, improved air-sealing technologies and advancing cold-climate heat pump technology. However, the slow process for regional harmonisation and improvement of minimum energy efficiency standards continues to provide a very weak investment signal that could otherwise enable significant energy efficiency gains with minimal incremental costs beyond existing building construction investments.

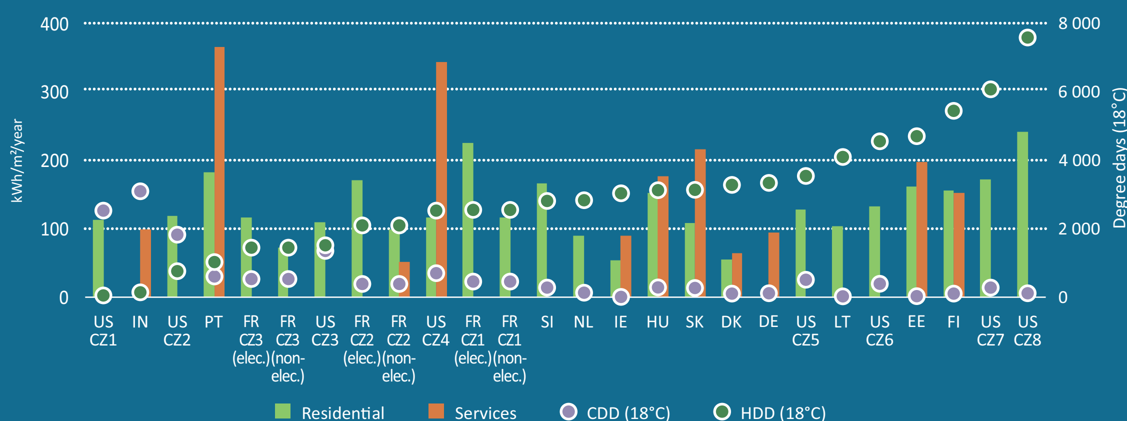
Recommended actions

Governments and industry should continue to fund R&D for energy-efficient technologies, including supporting international research through the IEA Technology Collaboration Programmes. Governments should also improve specifications for energy-efficient equipment and address existing building energy use by increasing funding for deep energy retrofit programmes, and accelerate deep retrofit activity in public buildings to demonstrate the potential and economic value of these retrofits.

2.41 Buildings energy code coverage



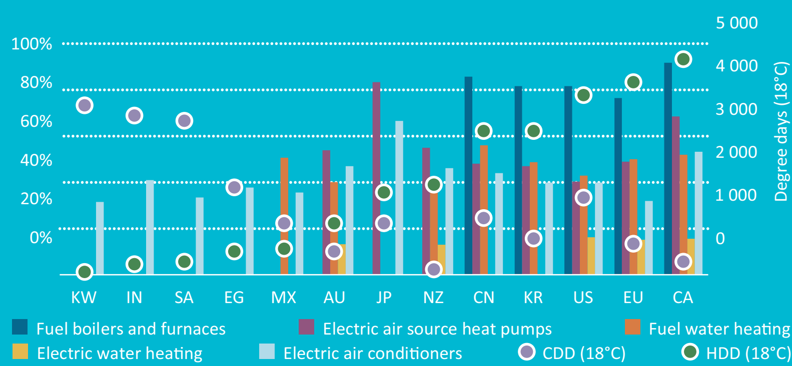
2.42 Minimum compliance with codes (primary energy)



4%

ANNUAL INCREASE IN SPACE COOLING SINCE 1990 – THE FASTEST GROWING END USE

2.43 Standards as a share of global best-in-class



For sources and notes see page 129

Appliances and lighting

● Improvement needed
↗ Positive developments

Proven achievements in energy efficiency standards and labelling (EESL) programmes should encourage their expansion across more countries and in a broadened range of product categories. Continued effort is needed to ensure that EESL programmes evolve with technology development to secure deployment of high-efficiency lighting, appliances and motors.

Recent trends

Global total final energy consumption for appliances, lighting and other equipment[19] continues to grow, although EESL programmes are helping to curtail energy demand growth. Evidence assembled in 2015 from a wide cross-section of countries with EESL programmes found that energy efficiency improvements in major appliances were around 3% to 4% per annum over a long period, compared with 0.5% to 1% per year for the underlying rate of technology improvement (4E TCP, 2015a). The most mature national EESL programmes are estimated to have saved as much as 25% energy consumption, depending on the country and the product.

Noteworthy in 2015 were requirements for transformers and water heaters that entered into force in the European Union and the United States (effective early 2016). Member states of ASEAN committed to regional harmonisation of lighting standards and policy – a decision expected to result in annual savings of 35 TWh of electricity (UNEP, 2015). The Clean Energy Ministerial Global Lighting Challenge also announced a race to reach global sales of 10 billion high-efficiency, high-quality and affordable lighting products as quickly as possible.

Growth in uptake and use of appliances, lighting and equipment continues to outpace the rate of energy efficiency improvements. This trend is especially true for televisions – whose ownership and average product size (e.g. average screen size) have reduced energy efficiency improvements – and other various plug loads (e.g. small appliances and electronics) that have continued rapid growth, often with no efficiency regulation. Despite policies designed to encourage more efficient appliances and equipment, technology choice has also meant missed opportunities for greater energy savings, as evidenced by the adoption of halogen lamps rather than compact fluorescent lamps (CFLs) or light-emitting diodes (LEDs) in the European Union. In other markets, such as the United States, adoption of LED lighting technology has increased rapidly in recent years.

"Smart" appliances and networked devices continue to grow in market share and have the potential to improve the way we manage energy, but they may also result in increased energy consumption if not managed properly, as shown in recent testing of smart lamps by the IEA Technology Collaboration Programme on Energy Efficient End-Use Equipment (4E TCP). Networked devices consume over 600 TWh globally (IEA, 2014), and this end use is growing rapidly. Policy responses to date have been varied for smart appliances and networked devices. One promising movement is the Connected Devices Alliance, comprising governments and industry formed under a G20 initiative in 2015, which aims to develop international approaches to maximise network-enabled energy savings and minimise the energy consumption from all networks and networked devices.

Tracking progress

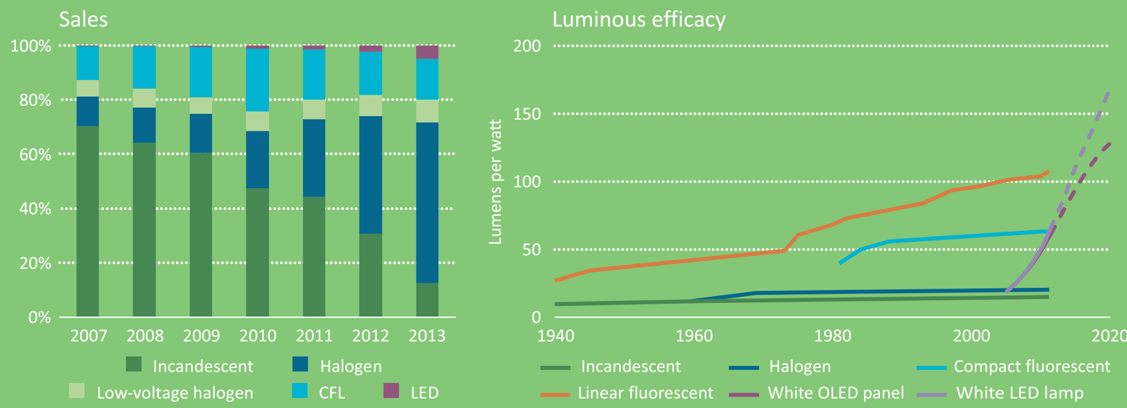
More than 80 countries have adopted some level of EESL for more than 50 types of appliances and equipment (4E TCP, 2015a), and more countries are either implementing or considering EESL programmes. Coverage of appliances and equipment continues to expand, although significant work is needed to address energy efficiency and product labelling for networked devices and other plug loads (e.g. portable electronics and small appliances). Electricity consumption growth needs to be halved, from the current 3% increase per year over the last decade to 1.5% in the 2DS.

Recommended actions

EESL programmes need regular review to ensure that efficiency requirements keep up with changes in technology and remain in line with policy objectives. Countries should focus on progressively increasing the stringency of EESL standards to promote continued uptake of high-efficiency technologies. This need for increased stringency includes monitoring of compliance and enforcement and expansion of existing EESL programmes to cover a broader range of products.

19 Other equipment includes pumps, motors, office equipment and other buildings-related electrical devices.

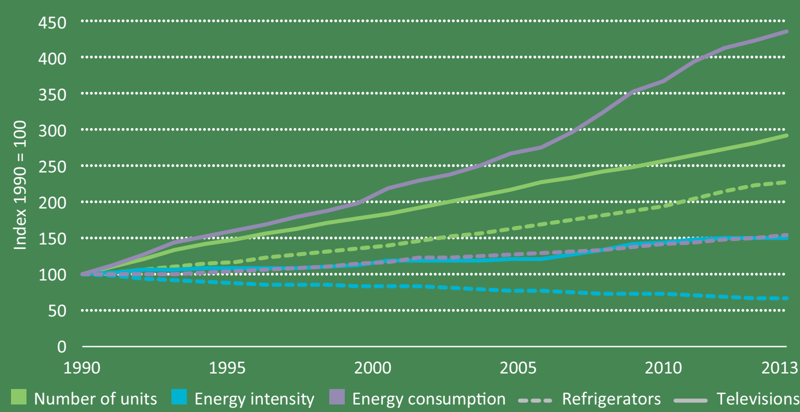
2.44 EU residential lighting sales and typical efficiencies



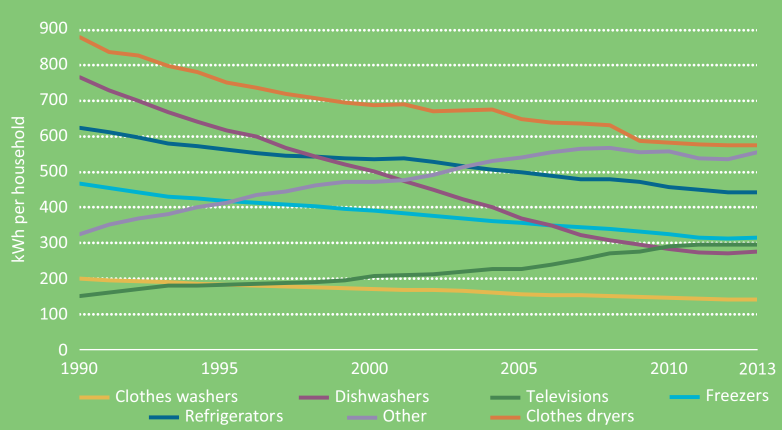
600

TWh ENERGY CONSUMPTION OF NETWORKED DEVICES WORLDWIDE IN 2013

2.45 World refrigerator and television energy use



2.46 World household appliance intensities



2DS REQUIRES ANNUAL GROWTH RATE OF ELECTRICITY FOR APPLIANCES AND EQUIPMENT TO

HALVE

FROM 3% TO 1.5%

For sources and notes see page 129

Solar heating

Not on track

~ Limited developments

Solar heat grew by an estimated 7% in 2014, but it still met less than 1% of global heat demand and needs to triple in absolute terms by 2025 to meet 2DS goals. Recent growth, however, has been significantly slower, and if challenging economics and inadequate support continue, solar heating will not be on track.

Recent trends

Despite an estimated 10% (35 gigawatt thermal [GW_{th}]) increase in cumulative capacity, annual deployment declined in 2014, almost by 20% compared to 2013, mostly due to slower economic growth and lower fossil fuel prices in major markets.[20] Global installed capacity reached an estimated 400 GW_{th} in 2014, although uncertainty exists over the exact figure due to data quality issues. Monitoring solar heat deployment is a challenge in many countries, because the small and fragmented nature of distributed technologies makes them difficult to track.

Annual deployment in China, the world's largest market, is estimated to have declined in 2014 for the first time in recent years due to a slowing economy and a weakening construction industry. With over 90% of the cumulative capacity in the residential sector, deployment has been slowing, and sustained solar heating growth in China will require faster uptake of larger systems for commercial and industrial applications.

Europe remained the second-largest solar thermal market in terms of cumulative capacity, but annual growth has also slowed recently as a result of the economic slowdown and inadequate policy support amid lower fossil fuel prices. To stimulate deployment, the French government reinvigorated its tax relief scheme in late 2014, and Germany reintroduced subsidies in April 2015. By contrast, growth continued in Turkey as it became the second-largest annual market in 2014, due to favourable resources and attractive economics for hot water systems. Elsewhere, other positive developments were seen in South America, the Middle East and southern Africa, where load shedding has driven the switch from electricity to solar thermal for water heating.

Over 95% of solar thermal heat is produced in the buildings sector, mostly from domestic hot water systems in single-family homes. By contrast, deployment for industrial process heat has been limited and concentrated mostly in lower-temperature applications. However, the increase in average system size by over 70% since 2007 reflects a growing market trend towards larger systems, where more favourable economics may be possible with higher and more constant heat demand. Chile commissioned the world's largest solar process heat plant (27 megawatts thermal [MW_{th}]) for copper mining in 2013, and Oman has announced plans to construct a 1 GW_{th} plant to produce steam for enhanced oil recovery operations. Solar thermal heat plays a marginal role in global district heat networks (less than 0.1%), except in Denmark where the largest solar thermal district heating plant (50 MW_{th}) was completed in 2015, and an even larger one (100 MW_{th}) is currently under construction.

Tracking progress

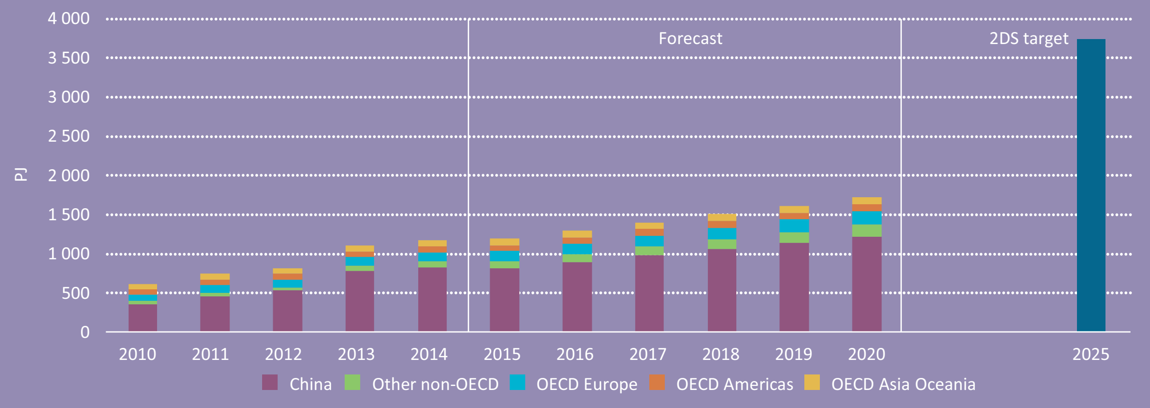
Despite robust growth over the last decade, solar thermal heat produced less than 1% of global heat demand in 2014 (around 1.2 EJ) and would have to more than triple in absolute terms by 2025 to meet the 2DS target. Achieving that goal, however, would require an annual deployment rate twice as fast as expected over the medium term, where annual additions are seen levelling off around 40 GW_{th} due to continued policy uncertainty and challenging economics. Without stronger and more widespread policy support, particularly for larger market segments, deployment trends will remain unchanged, and the 2DS 2025 target will not be reached.

Recommended actions

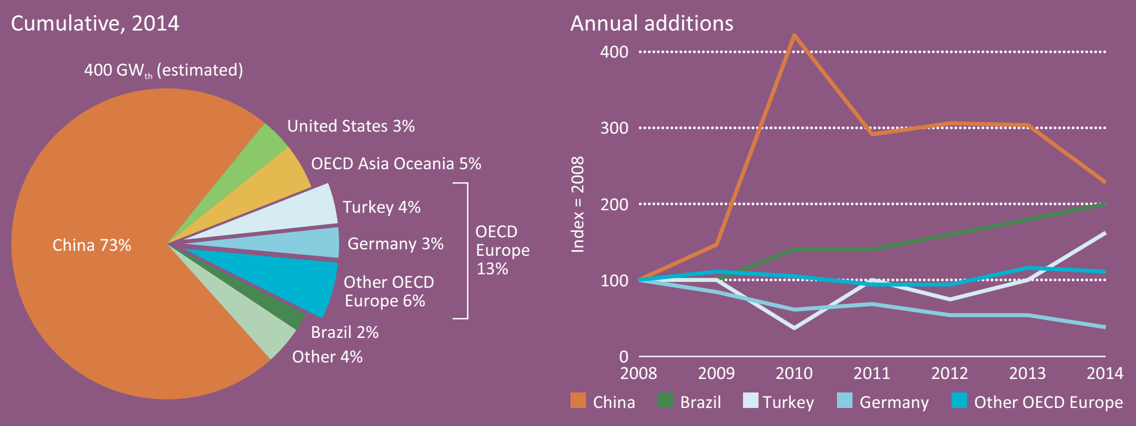
Governments should aim to create a stable, long-term policy framework for solar heating (including target setting and obligations), preferably in the context of an overarching strategy for renewable heat. Increased policy support is needed to scale-up investment across all solar heating market segments, particularly through mechanisms that increase their economic attractiveness against conventional heating technologies. Policy makers should ensure that financial incentives are adequate and consistent over a predictable period of time as well as promote innovative business models aimed at reducing high upfront costs.

20 Refer to Technology overview notes page 129 for notes associated with this section.

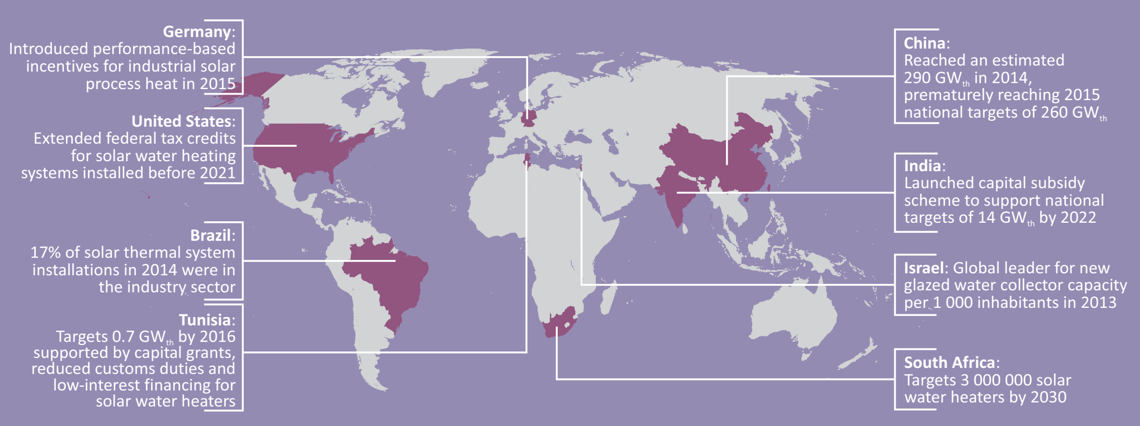
2.47 Solar thermal heat by region



2.48 Solar thermal capacity



2.49 Recent solar heating developments



For sources and notes see page 129

Co-generation and DHC

Improvement needed

~ Limited developments

Electricity generation using co-generation[21] technologies is stalled at less than 10%, despite increases in absolute terms. Efficient and integrated district heating and cooling (DHC) systems are promising, but significant progress is needed to capture this potential beyond select examples.

Recent trends

Global electricity and heat production[22] using co-generation technologies have increased on average by 1.2% per year since 2000, but not as fast as total electricity and commercial heat generation, which have grown at roughly 1.6% per year. Co-generation in global electricity production, therefore, decreased from 11% in 2000 to 9% in 2013, despite having a global average efficiency of 59% in 2013, compared with 37% for conventional thermal power generation.

District heat sales have grown steadily by roughly 1.2% per year since 2000, although district heat as a portion of buildings sector heat demand has remained relatively steady, increasing by only 0.3% per year since 2000. China is the world's largest network, and more than 90% of residents in north urban China are connected to district heat (IEA-TU, 2015). Performance of district heat varies by region, but globally the CO_2 intensity of district heat has improved only slightly since 2000. Coal and natural gas remain the dominant fuel choice for district heat production, although some countries have drastically reduced fossil fuel shares in district heat since 2000.

Globally district cooling networks continue to grow, with some countries, such as Sweden, increasing network length by as much as fourfold between 2000 and 2013 (Swedish District Heating Association, 2015). Data on progress are limited, as are overall data for improved understanding of CHP technologies and DHC network efficiency.

Notable progress in 2015 includes European Union efforts to assess multilevel actions for enhanced heating and cooling opportunities under the STRATEGO project.[23] China announced plans to assess industrial excess heat recovery potential for district heat in 150 cities (NDRC, 2015).

Tracking progress

Greater deployment of efficient and cost-effective co-generation and DHC could help to improve the emissions intensity of global electricity and heat production. Shifts away from conventional, inefficient power generation are critical to achieving 2DS targets, and CHP with modern, efficient DHC systems can help reduce primary energy demand and improve overall system efficiency. Advanced, integrated DHC systems can also facilitate a more flexible, integrated energy system, taking advantage of multiple potential low-carbon energy sources, such as variable renewables and industrial excess heat.

Recommended actions

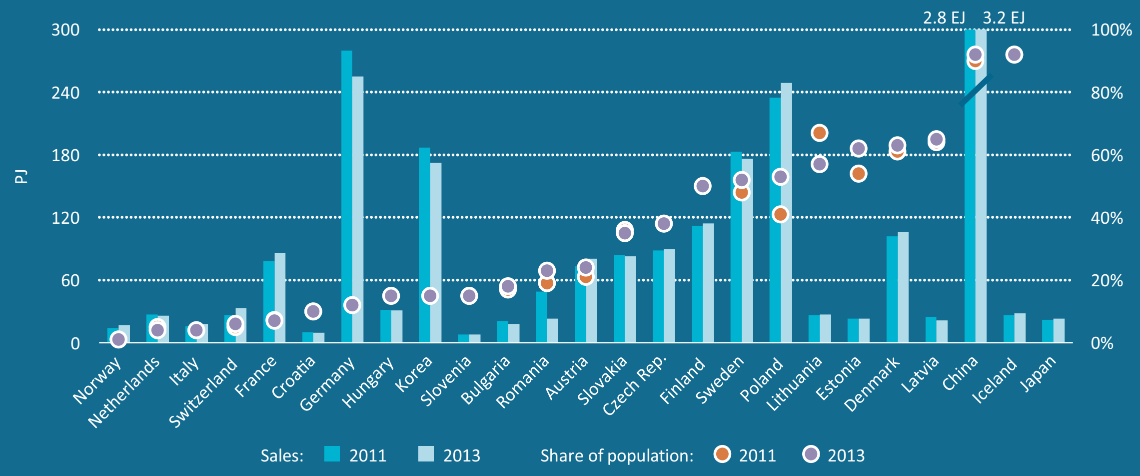
Data and improved resolution of co-generation and DHC technologies across the world's power generation, industrial and buildings sectors are critical to increase understanding of co-generation and DHC opportunities, which are typically a highly localised decision. Mapping of heating and cooling opportunities across the energy economy can also help to identify potential synergies and technology choices in electricity and heat generation.

Strategic planning of local, regional and national action should be pursued to identify cost-effective opportunities to develop co-generation and DHC networks in a more efficient, integrated energy system. Policy makers should remove market and policy barriers that prevent co-generation and DHC from competing as efficient and low-carbon solutions. Additional work is needed to address high upfront investment costs, inflexible business structures and lack of long-term visibility on policy and regulatory frameworks that limit co-generation and DHC.

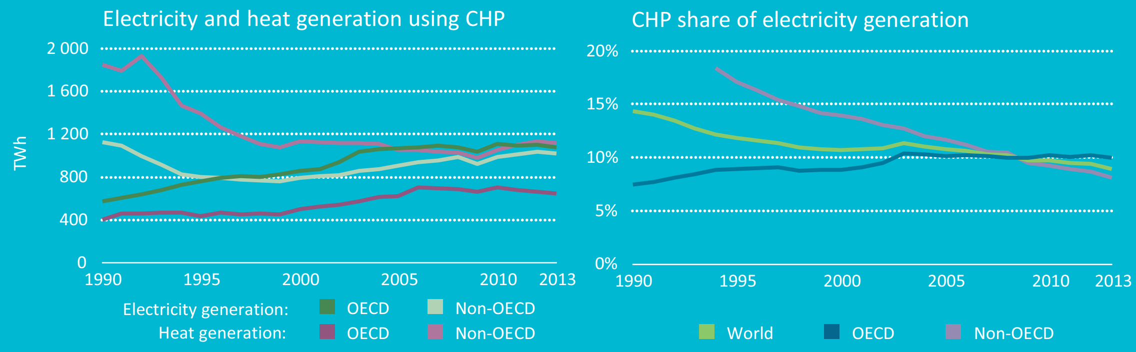
Further research is needed to improve understanding of the opportunities for co-generation and DHC under an increasingly dynamic, integrated energy system with various actors and energy sources. Improved understanding and enhanced strategies moving forward will help prevent lock-in of costly, long-lived decisions in electricity and heat generation in support of an efficient, low-carbon energy economy.

21-23 Co-generation refers to the combined production of heat and power. Refer to Technology overview notes page 130 for notes associated with this section.

2.50 District heat sales and share of population served



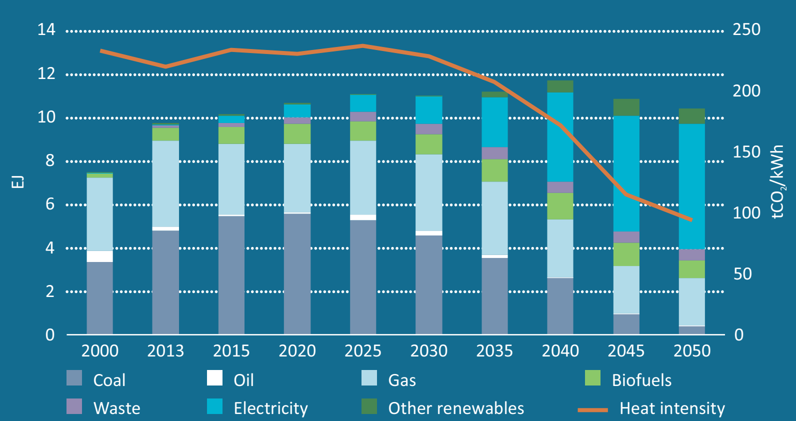
2.51 Co-generation trends



59%

GLOBAL AVERAGE EFFICIENCY OF CO-GENERATION IN ELECTRICITY PRODUCTION

2.52 District heating fuel mix and CO_2 intensity



For sources and notes see page 130

Smart grids

Improvement needed
~ Limited developments

Deployment of smart grid technologies has grown marginally compared to 2014 as smart meters reached saturation in many markets and investment in physical network assets waned. Information and operational technology (IT/OT) solutions are growth areas, increasing energy efficiency, power quality and network hosting capacity for clean energy.

Recent trends

The past year saw slowdowns in deployment of smart meters as some markets reached saturation, investment fell in distribution automation and other key new grid technologies, and uncertainties grew over the financial viability of incumbent utilities. As a result, annual growth in smart grid investment accelerated only marginally (BNEF, 2016). The widespread deployment of distributed generation is changing the load profiles typically seen by distribution network operators - putting pressure to invest in grid upgrades - and demand response enabled through advanced metering infrastructure (AMI) is gaining traction. However, regulatory frameworks do not always favour investment in innovative smart grid technologies.

Building on the first wave of AMI, utilities are looking for ways to implement business models based on 'big data' from highly distributed generation and load monitoring, increase the participation of energy consumers in electricity markets and enable demand side flexibility. Digital energy (IT/OT[24] solutions to improve operational capabilities of energy and network utilities) led growth in investment among all smart grid technology categories for network operators. The market for IT/OT solutions grew by 65% year-on-year (as anticipated in *TCEP 2015* [IEA, 2015k]) and is forecast to grow sixfold by 2023 (Navigant, 2014).

On the plant side, smart inverters for PV plants, wind farm automation, and control systems for wind- and PV-integrated energy storage, which reduce the impact of variable renewables (VRE) on distribution grids, are increasingly mandated through network codes. Distribution network operators in areas with high penetration of distributed and variable generation, including Germany, Italy and Hawaii (United States), are using smart grid technologies to monitor and control loads and generation. Among other benefits, these investments greatly reduce grid investment needs, or dramatically shorten permitting times for connecting distributed generation from weeks to near real time. Deployments in high-voltage transmission technology have kept a slower pace. Several projects for advanced high-voltage direct-current (HVDC) interconnection were inaugurated or close to completion, including the Belo Monte project in Brazil, a 2 GW Spain-France interconnection and an aggregate of 10 GW in China.

A recent emerging trend is the aggregation of loads and distributed generation to create "virtual power plants" (VPPs) and microgrids. VPPs can combine a rich diversity of independent resources into a network via sophisticated planning, scheduling, and bidding through IT-enabled smart technologies. Regional VPP demonstrations have been created in France (Nice Grid), Canada (PowerShift Atlantic) and the United States (Consolidated Edison of New York).

Tracking progress

Annual smart grid investments grew by 12% compared to 2014. IT-enabled solutions are increasing in importance as aggregators, VPPs and other business models based on physical smart grid infrastructure are expanding. Despite an increase in planned projects, large-scale interconnection has not kept up with the requirements in the 2DS, and some advanced HVDC technologies (e.g. voltage source converters and DC circuit breakers) required for interconnected DC grids are still to reach full market adoption.

Recommended actions

The increase in business models based on AMI and for distributed generation means strategies for smartening power grids need to be designed around customers and the opportunities opened up by big data. Key concerns remain for data privacy and security. Standard methods for accounting for the costs and benefits of smart grid technologies are still not widespread.

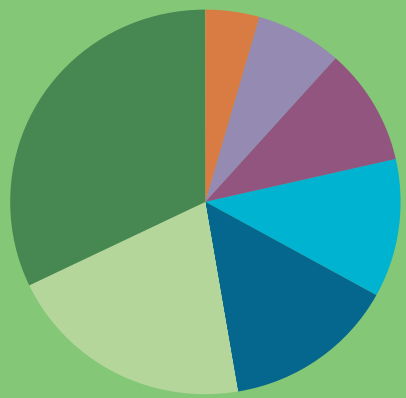
Inadequate interoperability and harmonisation of technology remain obstacles for smart grid technologies. Leveraging cross-sectoral interactions (e.g. power-to-heat, vehicle-to-grid [V2G]) requires a degree of interoperability not common in current practice.

24 IT refers to information technology (software component of a smart grid asset), whereas OT refers to operational technology (the physical component of a smart grid project).

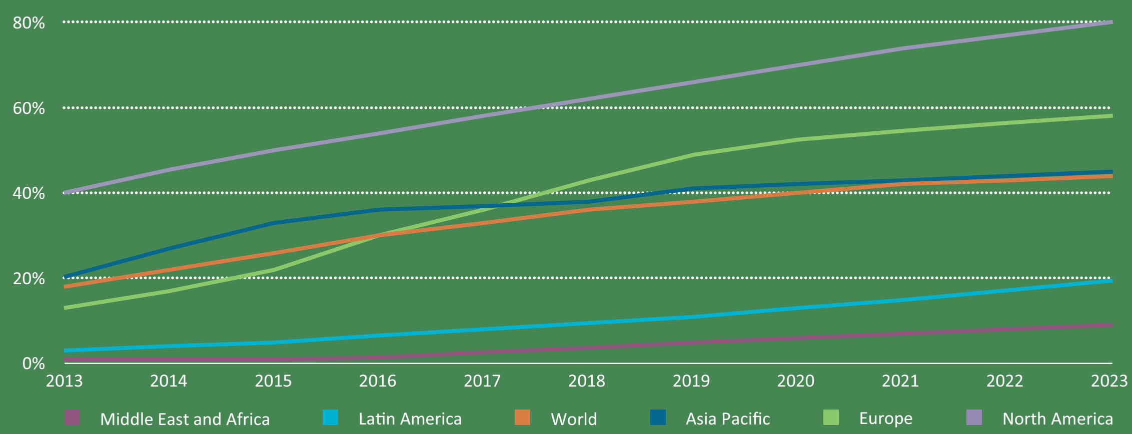
350

USD BILLION
POWER GRID INVESTMENT BY 2020 ANNOUNCED IN CHINA (30% OF 2DS WORLD TOTAL)

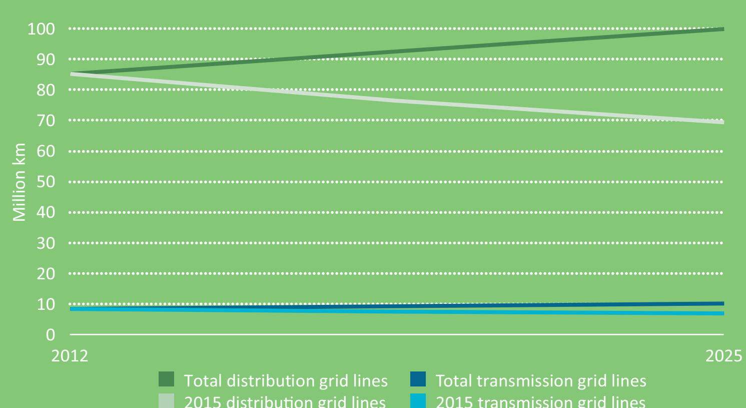
2.53 Projects by technology area



2.54 Smart meter penetration in key regions



2.55 Grid infrastructure in the 2DS



2.5

USD BILLION
NEW INVESTMENT IN TRANSMISSION AND DISTRIBUTION REQUIRED BY 2025 (45% OF POWER SECTOR TOTAL)

For sources and notes see page 130

Energy storage

● Improvement needed
↗ Positive developments

Storage plays an important role in the 2DS vision, providing flexibility to energy systems, increasing the potential to accommodate variable renewables and distributed generation, and improving management of electricity networks. Storage technologies experienced a landmark year in 2014, largely driven by policy action and regulatory changes.

Recent trends

Large-scale energy storage continues to be dominated globally by pumped hydropower, both in terms of installed capacity (149 GW, or 96% of the total) and of new installations (over 5 GW completed in 2014, or 72% of the total). Battery storage, however, was deployed strongly through 2014, with a record 400 MW additions, more than doubling the installed base in 2013. Regulators worldwide (particularly in the United States, Europe and key markets in Asia) have introduced mandates and other policy instruments to spur storage deployment within their jurisdictions. In liberalised markets, rule changes increasingly allow storage to compete in markets for services beyond wholesale energy trade (e.g. markets for capacity or frequency regulation). Finally, in a growing number of countries, policy and regulation are aiming to explicitly capture more value from distributed resources through policy instruments that are opening opportunities for storing excess power production locally (e.g. tariff designs for self-generated and exported power).

This accelerated deployment has been accompanied by continued and rapid reductions in technology costs in battery technology, particularly in lithium-ion (Li-ion) chemistries. Since 2010, costs have followed a similar trend to those experienced by PV a decade earlier, with learning rates[25] averaging 22%. Increasing evidence exists, however, that drivers for recent cost reductions may echo those that have shaped the boom in PV installations since 2011. In the medium term, once markets rebalance cost reductions are likely to continue – in large part, due to knowledge acquired from lithium-ion batteries powering electric vehicles and consumer electronics. Particular attention is required in the area of balance-of-system costs.[26] These costs can greatly affect total installed costs and depend on local capacities, not technology trends.

Building-scale power storage emerged in 2014 as a defining energy technology trend. The market grew by 50% year-on-year. The commercialisation of the Tesla Powerwall (a 10-kWh lithium-ion storage solution) captured public attention and pressured other manufacturers to reduce costs. Such behind-the-meter battery storage allows private consumers to improve the economic value of self-generated electricity. This trend is expected to accelerate as more consumers look to reduce grid electricity expenditures, reduce capacity charges and maximise consumption of self-generated power.

Beyond lithium-ion battery storage, however, progress in other areas remains weak. The deep decarbonisation of power generation envisaged in the 2DS requires technologies better adapted to storing large volumes of energy that can be converted back to electricity, to compensate for extended periods of abundant or scarce generation arising from high shares of wind and solar power. With around 40 MW of planned deployments, flow batteries have shown significant progress and could fulfil this role. Progress in larger-scale solutions such as compressed air energy storage or pumped hydro has been thwarted by planning constraints and a lack of viable business models.

Tracking progress

Lower-than-anticipated costs and policy developments have accelerated deployment in some energy storage fields such as grid-tied battery technology. High upfront costs, however, remain an obstacle to wider deployment. Data gaps remain, particularly in the emerging market of behind-the-meter storage.

Recommended actions

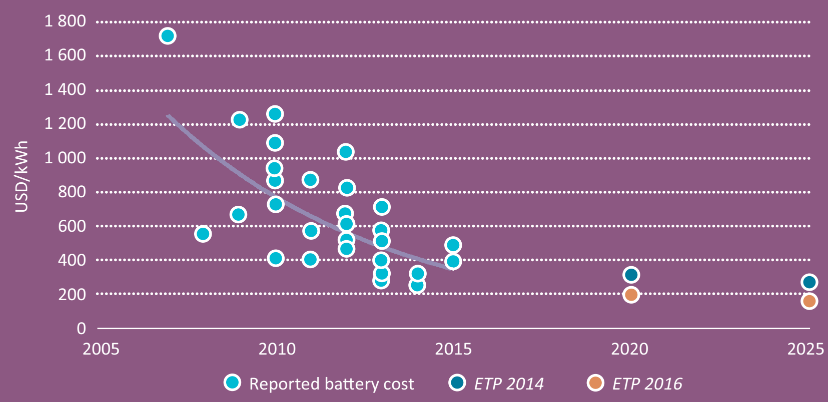
Market and regulatory frameworks that allow the energy system to capture the full benefits of storage must continue to be developed. These frameworks must reward how fast and how often a power system resource responds to changes in power supply or load. Particular attention is required in the area of integration of storage systems with existing grid infrastructure or with on-site power generation technologies. Training and capacity-building programmes, simplifying permitting schemes and better collection of market and technology data are also required.

25-26 Refer to Technology overview notes page 130 for notes associated with this section.

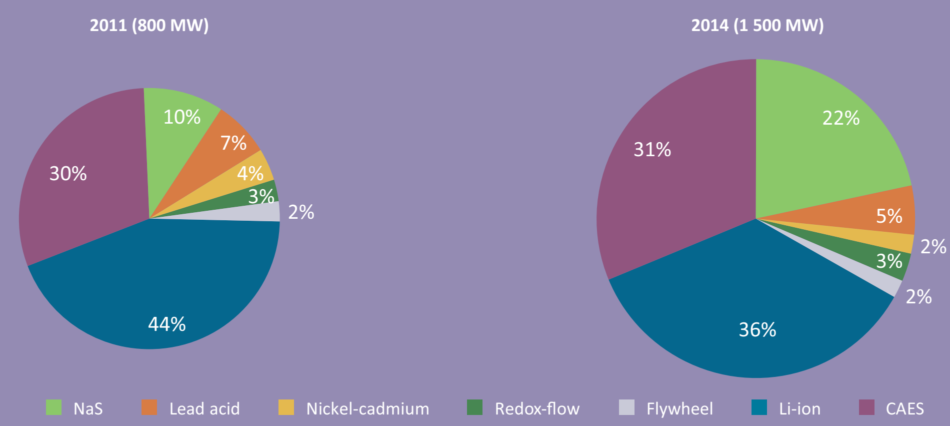
2.5

TIMES GROWTH IN UNITED STATES ENERGY STORAGE IN 2015

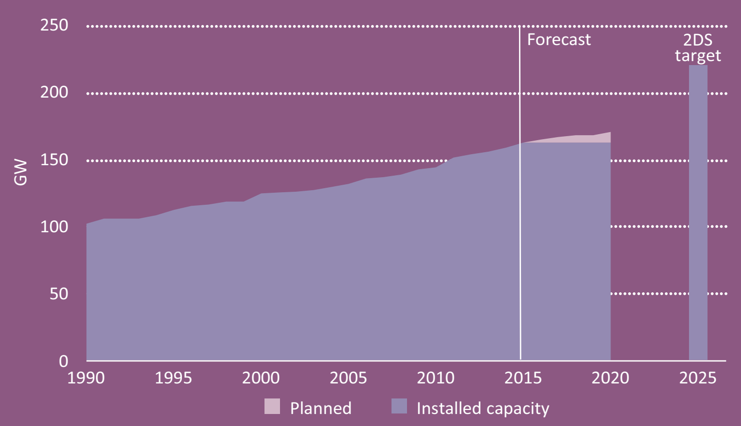
2.56 Large-scale battery investment cost



2.57 Large-scale battery storage



2.58 Pumped hydro storage



1.6 GW

LARGE-SCALE BATTERY STORAGE BUILT OR PLANNED

142 GW

PUMPED HYDRO STORAGE CAPACITY

For sources and notes see page 130

Technology overview notes

Unless otherwise noted, data in this report derive from International Energy Agency (IEA) statistics and *Energy Technology Perspectives* (*ETP*) analysis. The notes in this section provide additional sources and details related to data and methodologies.

Throughout the report, annual averages are calculated as compound average growth rates.

Renewable power (page 84)

Figures 2.2, 2.3, 2.6 and 2.7: sources: data from IEA (2015a), *Medium-Term Renewable Energy Market Report* and 2°C Scenario (2DS) targets from 2016 *ETP* model.

Figure 2.5: notes: Values reported in nominal United States dollars (USD) include preferred bidders, power purchase agreements or feed-in-tariffs. US values are calculated excluding tax credits. Delivery date and costs may be different than those reported at the time of the auction.

Nuclear power (page 90)

Figures 2.9 and 2.10: sources: data from IAEA (International Atomic Energy Agency) (2015), PRIS (Power Reactor Information System) database, www.iaea.org/pris/; NEA (Nuclear Energy Agency) and IAEA (2014), *Uranium 2014: Resources, Production and Demand (The Red Book)*.

Figure 2.11: notes: construction spans from first concrete-to-grid connection. Grid connection for projects under construction is estimated based on recent public information. FNR = fast neutron reactor; Gen II = second generation nuclear reactor; Gen III = third generation nuclear reactor; HTR = high temperature reactor; SMR = small modular reactor.

Figure 2.11: source: realised grid connection data from IAEA (2015), PRIS database, www.iaea.org/pris/.

Natural gas-fired power (page 92)

Figure 2.12: note: NBP = National Balancing Point (United Kingdom), representative of European gas prices.
Sources: Henry Hub: Intercontinental Exchange; NBP: GasTerra; Japan LNG: Japan Customs.

Figure 2.13: note: other fossil category comprises coal-fired power and oil-fired power generation. Oil-fired power generation is negligible in Germany and the United States (<1%), but represented 11% in Japan in 2014.

Figure 2.14: note: the capacity factor describes the output from the plant over a period of time relative to the potential maximum output; it depends on both the running time and the operating load.

Coal-fired power (page 94)

Figure 2.16: note: other renewables includes geothermal, solar, wind, ocean, biofuels and waste.

Figure 2.17: note: gCO_2/kWh = grammes CO_2 per kilowatt hour.

Carbon capture and storage (page 96)

Note 3: Enhanced oil recovery (EOR) is a closed-cycle process that involves injecting carbon dioxide (CO_2) into older oil reservoirs to increase or prolong production. The CO_2 is injected into the reservoir, recovered from the produced oil and re-injected. CO_2 is retained and eventually stored through injection for EOR, though additional monitoring and planning is needed to ensure the CO_2 is effectively stored. The IEA has recently defined what it considers as the criteria for planning and monitoring to ensure the efficacy of storage through EOR in IEA (2015c), *Storing CO_2 through Enhanced Oil Recovery*, OECD/IEA, Paris. To date, very few EOR projects meet these criteria.

Figure 2.18-2.19: note: Large-scale projects are defined in accordance with the Global Carbon Capture and Storage Institute (GCCSI), i.e. projects involving the annual capture, transport and storage of CO_2 at a scale of at least 800 000 tonnes of CO_2 (tCO_2) for a coal-based power plant, or at least 400 000 tCO_2 for other emissions-intensive industrial facilities (including natural gas-based power generation). Advanced stage of planning implies that projects have reached at least the "Define stage" in accordance with the GCCSI Asset Lifecycle Model.

Figure 2.18-2.19: source: GCCSI (2015), *The Global Status of CCS 2015*.

Figure 2.20: note: data are in USD 2014 prices and purchasing price parity (PPP).

Industry (page 98)

Note 2: Industry energy consumption includes energy use in blast furnaces and coke ovens and as petrochemical feedstock.

Note 3: In IEA modelling, five energy-intensive sectors are considered: chemicals and petrochemicals, cement, iron and steel, aluminium, and pulp and paper.

Figure 2.21: note: chemicals and petrochemicals includes fuel use as petrochemical feedstock.

Figure 2.22: note: Direct energy-related CO_2 emissions are those from fuel combustion. In chemicals and petrochemicals, there is a slight increase in direct energy-related CO_2 intensity in 2025 primarily due to the effect of existing and planned coal-based methanol-to-olefins capacity in the short term in China, with a greater overall energy footprint than steam cracking. Emissions from electricity generation are accounted for in the electricity sector, making electricity-intensive industrial processes appear less CO_2-intensive.

Aluminium (page 100)

Note 4: This represents aluminium produced from new and old scrap. Internal scrap has been excluded for consistency with published statistics.
Source: IAI (International Aluminium Institute) (2015b), *Global Mass Flow Model – 2013 (2014 draft)*, www.world-aluminium.org/publications/.

Note 5: This represents the share of production based on new and old scrap. Internal scrap has been excluded for consistency with published statistics.
Source: IAI (2015b), *Global Mass Flow Model – 2013 (2014 draft)*, www.world-aluminium.org/publications/.

Note 6: These data are reported by IAI member companies and associations to IAI, and capacity not covered by members is accounted for via IAI estimates. Alumina refining energy intensity does not include alternative (non-Bayer) processes.
Source: IAI (2015a), *Current IAI Statistics*, www.world-aluminium.org/statistics/ (accessed 7 December 2015).

Note 7: Of which aluminium is a major part. Not all of the increase in energy consumption can be attributed to aluminium. Defined in the IEA Energy Balances as ISIC Group 242 (manufacture of basic precious and other non-ferrous metals) and Class 2432 (casting of non-ferrous metals).
Sources: IEA (2015e), *Energy Balances of OECD Countries*, OECD/IEA, Paris; United Nations Statistics Division (2008), *International Standard Industrial Classification of All Economic Activities (ISIC)*, Rev. 4, Series M No. 4, UNSD, New York.

Note 8: These data are reported by IAI member companies and associations to IAI, and capacity not covered by members is accounted for via IAI estimates. Best available technology (BAT)

level for primary aluminium smelting is given as 49 gigajoules per tonne (GJ/t) aluminium (Al) (13 611 kilowatt hours per tonne [kWh/t] Al), and BAT level for Bayer process alumina refining is 7.6 GJ/t alumina.
Sources: IAI (2015a), *Current IAI Statistics*, www.world-aluminium.org/statistics/ (accessed 7 December 2015); LBNL (Lawrence Berkeley National Laboratory) (2008), *World Best Practice Energy Intensity Values for Selected Industrial Sectors*, LBNL, Berkeley.

Note 9: A recent estimate put overall average energy intensity of alumina refining in China at 18.53 GJ/t.
Source: Rock, M. and M. Toman (2015), *China's Technological Catch-up Strategy: Industrial Development, Energy Efficiency, and CO_2 Emissions*, Oxford University Press, Oxford.

Note 10: This could be commercially available by 2030, by some estimates, though this depends on research progress in creating an economically and technically viable inert anode. Intergovernmental Panel on Climate Change (IPCC) literature estimates availability by 2020. Note that in IEA modelling, inert anodes are assumed to be commercially available from 2030 in the 2DS, and 2035 in the 4°C Scenario (4DS).
Source: IPCC (2007), *Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.

Note 11: Refer to IEA (2015f), *World Energy Outlook 2015,* OECD/IEA, Paris, for additional discussion of material efficiency in the aluminium sector.

Textbox: note 12: this represents the share of production based on new and old scrap in 2025 in the 2DS. Internal scrap has been excluded for consistency with published statistics.

Figure 2.24: note: GCC = Gulf Co-operation Council. These data are reported by IAI member companies and associations to IAI, and capacity not covered by members is accounted for via IAI estimates. For regional definitions see source website.
Source: IAI (2015a), *Current IAI Statistics*, www.world-aluminium.org/statistics/ (accessed 7 December 2015).

Figure 2.25: note: Bubble size refers to primary aluminium production in millions of tonnes (Mt). These data are reported by IAI member companies and associations to IAI, and capacity not covered by members is accounted for via IAI estimates. For regional definitions see source website. Alumina refining energy intensity includes only Bayer process refining, which means some regions' refining energy intensities are underestimated in this graph, particularly China. BAT level for alumina refining energy intensity is 7.6 GJ/t alumina, and for smelting electricity intensity is 13 611 kWh/t Al. BAT levels refer to an average size capacity, and the achievable performance level not considering particular characteristics at specific sites, such as high capacity sites with high levels of process integration, and varying qualities of raw materials and feedstocks.
Source: IAI (2015a), *Current IAI Statistics*, www.world-aluminium.org/statistics/ (accessed 7 December 2015).

Figure 2.26: note: includes top six primary aluminium producing regions. CO_2 intensities of electricity production are based on national averages, not electricity provided specifically to the aluminium sector. In the 2DS, as global electricity supplies become increasingly decarbonised, several of these regions' CO_2 intensities of electricity production reach nearly zero. In 2025, Canada reaches 73 grammes CO_2 per kilowatt hour (gCO_2/kWh), Brazil reaches 26 gCO_2/kWh and Norway reaches 6 gCO_2/kWh. Norway also starts from a very low level, 8 gCO_2/kWh, due to the large share of hydropower in its primary energy supply.
Sources: IEA analysis; USGS (United States Geological Survey) (2015), *Minerals Yearbook: Aluminum*, www.minerals.usgs.gov/minerals/pubs/commodity/aluminum/index.html#myb.

Transport (page 102)

Note 13: Well-to-wheel refers to the energy use and greenhouse gas (GHG) emissions in the production of a fuel and its use in a vehicle. Well-to-wheel energy use and GHG emission estimates exclude the production and end-of-life disposal of the vehicle and fuel production/distribution facilities. As such, they provide a partial view of energy use and emissions resulting from a life-cycle assessment (LCA) of fuel and vehicle production, use and disposal. LCA is a broader concept, requiring more information than the well-to-wheel energy and GHG emissions estimates. LCA is used to account for all the environmental impacts (not only energy and GHG, but also many kinds of pollutants and water requirements) resulting from the consumption of all the materials needed for the production process.

Figure 2.27: note: $MtCO_2$-eq = million tonnes of carbon dioxide equivalent; HFTs = heavy freight trucks; LCVs = light commercial vehicles; MFTs = medium freight trucks; pkm = passenger kilometres; tkm = tonne kilometres.
Source: IEA (2016a), *Mobility Model*, January 2016 version (database and simulation model), www.iea.org/etp/etpmodel/transport/.

Figure 2.28: note: this map is without prejudice to the sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.
Source: Population data sourced from UN DESA (United Nations Department of Economic and Social Affairs) (2014), *World Urbanization Prospects: The 2014 Revision*, CD-ROM edition, www.esa.un.org/unpd/wup/CD-ROM/ (accessed 10 October 2015); calculations derived from IEA (2015g), "World energy balances", *World Energy Statistics and Balances 2015* (database), www.iea.org/statistics (accessed 4 February 2016).

Electric vehicles (page 104)

Figure 2.29: note: BEV = Battery Electric Vehicle; PHEV = Plug-in Hybrid Electric Vehicle.

Figure 2.29-2.30: source: IEA (forthcoming), *Global EV Outlook 2016*.

Figure 2.31: note: reflects a share of electric driving for plug-in hybrid electric vehicles of 30%.
Source: IEA (forthcoming), *Global EV Outlook 2016,* OECD/IEA, Paris; IEA (2015h), *CO_2 Emissions from Fuel Combustion* (database), www.iea.org/statistics; IEA (2016a), *Mobility Model*, January 2016 version (database and simulation model), www.iea.org/etp/etpmodel/transport/.

Aviation (page 106)

Note 15: Unless otherwise noted, all references to energy use are expressed in terms of final energy.

Note 16: In aviation, the common activity metric is RPK: revenue passenger-kilometres. This corresponds to the number of passengers transported, multiplied by the kilometres they fly. It is equivalent to passenger-kilometres (pkm) in other transport modes.

Note 17: Air Transport Action Group (ATAG) represents a broad industrial consortium in aviation, including airport operators, aircraft and aircraft engine manufacturers, airlines, and civil aviation services, among others.

Figure 2.32: source: Calculations derived from IEA (2015g), *World Energy Statistics and Balances 2015*, www.iea.org/statistics; ICAO (International Civil Aviation Organization) (2013), "Appendix 1", *Annual Report of the ICAO Council: 2013*, www.icao.int/annual-report-2013/Documents/Appendix_1_en.pdf.

Figure 2.33: note: GDP = gross domestic product.
Source: IEA (2016a), *Mobility Model*, January 2016 version (database and simulation model), www.iea.org/etp/etpmodel/transport/; population calculations from UN DESA (2014), *World Urbanization Prospects: The 2014 Revision*, www.esa.un.org/unpd/wup/CD-ROM/.

Figure 2.33-2.34: source: IEA (2016a), *Mobility Model*, January 2016 version (database and simulation model), www.iea.org/etp/etpmodel/transport/.

Biofuels (page 108)

Note 18: Sustainably produced biofuels offer a lower-carbon intensity alternative to petroleum-derived fuels. Conventional biofuels include sugar- and starch-based ethanol and oil crop-based biodiesel. Advanced biofuels include biofuels based on non-food agricultural residue and waste feedstocks such as cellulosic ethanol, renewable diesel and bio-synthetic gas. The category also includes other novel technologies that are mainly in the research and development and pilot stages.

Flexible-fuel vehicles, or flex-fuel vehicles, have suitable engine modifications to use higher ethanol blends (e.g. E85) or as is commonly found in Brazil, pure hydrous ethanol (E100). As of February 2016, ten commercial-scale advanced biofuels plants have been commissioned in Brazil, China, Europe and the United States; annual production capacities for these plants range from 30 to 120 million litres per year. Nine of these plants produce cellulosic ethanol from biomass wastes and agricultural residues.

Examples of ambitious and long-term transport sector targets include Finland's aim to provide a 40% share of renewable transport fuels and Sweden's goal of a vehicle stock independent of fossil fuels, both by 2030. Examples of policies to establish defined reductions in the life-cycle carbon intensity of transportation fuels include the Low Carbon Fuel Standard in California and the Climate Protection Quota in Germany. These policies take into effect the different levels of carbon reduction achieved by biofuels due to specific feedstock and production process combinations. Specific advanced biofuels quotas are included in the Renewable Fuel Standard in the United States, will be introduced in Italy from 2018 and are under consideration within several other European countries.

Both conventional and advanced biofuels' contributions to the 2DS have been revised down from previous projections due to slower market growth and lower than anticipated commercialisation, respectively. This reduction is offset by updated transport assumptions regarding journey avoidance and switching to alternative public transport modes in urban areas, in addition to a slower assumed GHG emissions reduction profile and updated vehicle efficiency assumptions.

Figure 2.35: sources: IEA (2016b), *Medium-Term Oil Market Report 2016*; 2DS targets from the 2016 *ETP* model.

Figure 2.36: source: Biofuels production data from IEA (2016b), *Medium-Term Oil Market Report 2016*.

Figure 2.37: source: Bloomberg New Energy Finance (BNEF) (2015), *Funds Committed* (database), www.bnef.com/FundsCommitted/search.

Buildings (page 110)

Figure 2.39: notes: the year 1995 has been used for the Russian Federation to account for the dissolution of the Former Soviet Union. MWh = megawatt hours.

Figure 2.40: note: kWh/m^2 = kilowatt hours per square metre; ASEAN = Association of Southeast Asian Nations.

Building envelopes and equipment (page 112)

Figure 2.41: note: this map is without prejudice to the sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.
Source: IEA building code analysis and IEA (2015i), *IEA Building Energy Efficiency Policies (BEEP) Database,* www.iea.org/beep/.

Figure 2.42: note: heating and cooling degree days are based on average heating degree days (HDD) over the heating region within a large country and average cooling degree days (CDD) over the cooling region within a large country. CZ = climate zone, as defined by Ministère de l'Environnement, de l'Énergie et de la Mer [Ministry of the environment, energy and the sea] (2013) and Pacific Northwest National Laboratory (PNNL) (2015).
Source: IEA building code analysis and Global Buildings Performance Network (GBPN) analysis; Ministère de l'Environnement, de l'Énergie et de la Mer [Ministry of the environment, energy and sea] (2013), *La répartition des départements par zone climatique [The distribution of departments by climate zone];* PNNL (2015), *High-Performance Home Technologies: Guide to Determining Climate Regions by County*, Building America Best Practices Series.

Figure 2.43: note: fuel boilers are not compared with gas heat pumps in this figure. HDDs and CDDs are based on average HDD over the heating region within a large country and average CDD over the cooling region within a large country.
Source: IEA technology policy mapping analysis.

Appliances and lighting (page 114)

Figure 2.44: note: CFL = compact fluorescent lamp; LED = Light emitting diode; OLED = organic light emitting diode.

Figure 2.44 (left): source: 4E TCP (Technology Collaboration Programme on Energy Efficient End-Use Equipment) (2015b), "Mapping & benchmarking of the impact of 'phase-out' on the lighting market (updated)", www.iea-4e.org/document/351/policy-brief-mapping-benchmarking-of-the-impact-of-phase-out-on-the-lighting-market-updated.

Figure 2.44 (right): source: adapted from US-DOE (United States Department of Energy) (2012), *Solid-State Lighting Research and Development: Multi-Year Program Plan*.

Solar heating (page 116)

Note 20: Data for total installed global solar thermal collector capacity are estimated, with a considerable amount of uncertainty over the coverage in some markets. For this report, several data sources were used including official IEA statistics, Technology Collaboration Programme on Solar Heating and Cooling (SHC TCP), the European Solar Thermal Industry Federation (ESTIF), and national administrations. Data for 2014 deployment are preliminary and may differ from when historical data sources are updated.

Solar thermal collector capacities are represented in gigawatts thermal (GW_{th}) using the conversion factor of 0.7 kilowatts thermal per square metre (kW_{th}/m^2) to derive the nominal capacity from the area of installed collectors in order to make solar thermal collector capacity comparable with that of other energy sources. The conversion factor was agreed by representative associations from member countries, the ESTIF and the IEA SHC programme in a 2004 joint meeting between the SHC TCP and major solar thermal trade associations.

Figures 2.47, 2.48 and 2.49: sources: data from IEA (2015j), *Renewables Information 2015* www.iea.org/statistics/; SHC TCP (2015), *Solar Heat Worldwide*; ESTIF (2015), *Solar Thermal Markets in Europe;* and 2DS targets from 2016 *ETP* model.

Figure 2.49: note: this map is without prejudice to the sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

Co-generation and district heating and cooling (page 118)

Note 21: Cogeneration is also commonly referred to as combined heat and power (CHP). This report uses the term "cogeneration" to refer to the simultaneous generation of heat and electricity.

Efficiency for a district cooling system refers to the ratio of final thermal energy provided to primary energy input for generation. These efficiencies can be especially high in the case of systems that use surplus heat and natural cooling sources as inputs.

Note 22: According to IEA energy balance conventions, for auto-producer cogeneration plants, which produce some heat and electricity for their own use, only heat generation and fuel input for heat sold are considered, whereas the fuel input for heat used within the auto-producer's establishment is not included, but accounted for in the final energy demand of the appropriate consuming sector. Transmission and distribution losses are not included.

Note 23: More information is available at www.stratego-project.eu/project-brief/.

Figure 2.50: notes: share of population served by district heat in China accounts only for populations in north urban China. Estimates provided by the Tsinghua University Buildings Energy Research Center (BERC).
Sources: Euroheat & Power (2015), *District Heating and Cooling: Country by Country Survey 2015*; TU (Tsinghua University) (2015), *2015 Annual Report on China Building Energy Efficiency*.

Figure 2.51: notes: non-OECD CHP shares have not been included for 1990-93 due to the dissolution of the Former Soviet Union. Heat generation includes heat sold and does not include heat used on-site.

Figure 2.52: note: decarbonisation of district heating accelerates in the medium- to long-term time frame given the volumes of infrastructure already in place to 2025 and the typical lifetimes of heat generation investments.

Smart grids (page 120)

Figure 2.53: note: DER = distributed energy resources; V2G = vehicle to grid; VRE = variable renewables.
Source: ISGAN (International Smart Grid Action Network) (2015), *Global Smart Grid Inventory*.

Figure 2.54: note: see page 402 for deviations from regional groupings associated with this figure.
Source: Navigant (2014), *Smart Grid Technologies*.

Figure 2.55: source: IEA analysis and NRG Expert (2015), *Electricity Transmission and Distribution Report and Database*, www.nrgexpert.com/energy-market-research/electricity-transmission-and-distribution-report-and-database/.

Energy storage (page 122)

Note 25: The technology learning rate refers in this case to the reduction in investment costs for every doubling of cumulative (historical) installed capacity.

Note 26: "Balance-of-system costs" refers to costs related to additional equipment and operations required to monitor, manage and connect batteries to power grids.

Figure 2.57 and top row textbox: source: IEA analysis and US-DOE (2016, *Global Energy Storage Database*, www.energystorageexchange.org/.

Figure 2.57: note: NaS = sodium sulphur; Li-ion = lithium ion; CAES = compressed air energy storage.

Figure 2.58: source: Platts (2015), *World Electric Power Plants Database*.

Bottom row textbox: source: GTM (Greentech Media) (2016), *US Energy Storage Monitor*.

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Part 2

Towards Sustainable Urban Energy Systems

Cities are density centres for global energy demand and are responsible for a significant share of carbon emissions, expected to increase with growing urban populations and urban economic activity. However, a wide range of solutions exists to reduce the carbon footprint and improve the overall energy sustainability of urban areas.

The chapters in Part 2 look at how urban systems can turn from being drivers of unsustainable trends to strategic pillars of an ambitious low-carbon energy transition. Compact urban development, energy-efficient buildings, public transport, low-carbon end-use fuels, distributed renewable energy and smart energy networks all offer a vast and largely untapped potential to effectively achieve energy sustainability in cities.

Local and national policy makers need to increase their efforts and work together to ensure that the right conditions are in place to enable cities to achieve their energy sustainability potential. Part 2 ends with a chapter on Mexico, which can show the world that with the right commitment of national and sub-national governments, cities can drive decarbonisation.

Chapter 3 **The Urban Energy Challenge** **137**

Urban areas can play a decisive role in the transition to a cleaner energy future. Shifts to more efficient buildings, transport systems and industrial processes; lower-carbon energy supplies; and integrated energy systems are critical. Enabling these shifts will require strong urban energy policies and increased co-operation between national and local governments.

Chapter 4 **Energy-Efficient Buildings in the Urban Environment** **171**

Rapid expansion of the global built environment and ownership of energy-using technologies will have a major impact on building energy use to 2050. Urban areas offer an important opportunity to improve building energy efficiency and realise low-carbon, integrated communities.

Chapter 5 **Sustainable Urban Transport** **217**

Meeting the growing demand for urban mobility while at the same time reducing carbon emissions will require a strong effort to reduce transport activity, shift to a greater use of public transport and deploy low-carbon technologies in cities. To realise this transition, local and national policy makers need to implement a broad portfolio of measures.

Chapter 6 **Energy Supply in Cities** **261**

Local clean energy supply is a prerequisite for greater energy sustainability in cities. Decentralised low-carbon electricity and heat generation within or close to urban areas, as well as smart urban energy networks, can play an important role in meeting multiple energy sustainability goals.

Chapter 7 **Policy and Finance Mechanisms for Urban Areas** **305**

Mobilising the urban sustainable energy potential requires leveraging a range of policy and finance mechanisms available to local authorities. Efforts are needed to enhance local capacity to implement effective policies, and national governments have a strategic role to enable cities to achieve their potential.

Chapter 8 **Mexico's Sustainable Energy Transition: The Role of Cities** **341**

Mexico has embarked on an ambitious decarbonisation path that will require a significant acceleration of low-carbon technology deployment. This transition can be achieved only if Mexican cities are enabled to successfully foster energy efficiency and cleaner fuels in urban energy systems.

Chapter 3

The Urban Energy Challenge

Urban areas can play a decisive role in the transition to a cleaner energy future. Sustainable urban energy systems can improve energy security and resilience while delivering multiple benefits for the environment, human health and economic growth. Shifts to more efficient buildings, transport systems, and industrial processes; lower-carbon energy supplies; and integrated energy systems are critical. Enabling these shifts will require strong urban energy policies and increased co-operation between national and local governments.

Key findings

- ***The world's economic activity and population will be increasingly concentrated in urban areas.*** *Global gross domestic product (GDP) will triple from 111 trillion United States dollars (USD) in 2015 to USD 337 trillion in 2050, when 84% of GDP will be generated by urban areas. Over the same period, the world's urban population will grow by 62% from 3.9 billion to 6.3 billion, with most growth occurring in developing and emerging economies.*
- ***Urban areas dominate global primary energy use and CO_2 emissions.*** *In 2013, the world's urban areas accounted for about 365 exajoules (EJ) of primary energy use (64% of global primary energy use) and about 24 gigatonnes (Gt) of carbon dioxide (CO_2) emissions (70% of the global total). Within urban areas, major sources of f nal energy demand are residential and services buildings, industrial processes, transport systems, and generation of electricity and heat.*
- ***Near-term policy actions must be taken to avoid "lock-in" of inefficient urban energy systems during upcoming periods of rapid urban population and GDP growth.*** *If current trends continue, global urban primary energy use would grow by about 70% – from 365 EJ in 2013 to 621 EJ in 2050 – while global urban CO_2 emissions also grow rapidly, from 23.8 Gt in 2013 to 35.7 Gt in 2050, an increase of about 50%.*
- ***With strong policy action and accelerated technology deployment, urban energy use and CO_2 emissions can be reduced significantly.*** *Global urban primary energy use can be limited to 431 EJ by 2050, representing only an 18% increase from 2013, while urban populations are projected to increase by 67% and urban GDP by 230% over the same time period. Global urban CO_2 emissions are also decoupled from energy use, limiting urban CO_2 emissions to 8.7 Gt in 2050, which is a 63% reduction from 2013 levels.*
- ***Achieving the 2DS for urban buildings and transport systems would not place significant burdens on the global economy.*** *Additional cumulative investments (compared to the 6DS) are estimated at USD 11 trillion between 2013 and 2050 for urban buildings and at negative USD 21 trillion for urban transport systems. Avoid and shif strategies in urban transport systems lead to signif cant reductions in passenger vehicle purchases and related infrastructure investments.*

- ***More energy and emissions data are needed at the urban scale.*** *Such data are critical to identify major contributors to urban energy use and emissions, establish energy and emissions baselines, prioritise policy actions, and monitor and communicate progress towards national and local energy and emissions goals.*
- ***The transition to sustainable urban energy systems must encompass all energy supply and end-use sectors.*** *Change will be driven by improved thermal performance and equipment efficiencies in the buildings sector; more compact urban forms and "Avoid/ Shif /Improve" strategies in the transport sector; greater use of combined power, heat and cooling systems; renewables; smart grids; and energy efficiency improvements in the industrial sector.*

Opportunities for policy action

- *National and local governments must implement new co-operative governance structures that strengthen the enabling environment for sustainable energy system technologies at the urban scale. Opportunities include greater alignment among national, regional and local policies (vertical integration) and greater collaboration and co-operation between local agencies (horizontal integration), to simultaneously meet environmental, economic and social objectives at both local and national levels. These actions are particularly important for small and medium cities, where local capacities are limited, and in emerging and developing economies.*
- *Enable cities to act as innovation hubs for sustainable urban energy system technologies and strategies by supporting public-private partnerships and technology demonstrations, and by communicating results and best practices to accelerate broader adoption of clean energy solutions.*
- *Develop and communicate comprehensive urban action plans that address multiple sustainability goals and def ne transparent objectives, metrics and targets over the short and long term, while conducting regular monitoring and evaluation of progress.*
- *Invest in long-term data capabilities that provide robust energy statistics at urban scales, and across all major energy demand and supply sectors, to more accurately track urban energy system progress; invest in modelling capacities to provide robust analytical guidance for energy technology and energy policy decisions.*
- *Increase research, development and deployment (RD&D) investment in core technology areas necessary for sustainable urban energy systems, including advanced building and mobility technologies, integrated power, heat, and cooling technologies, smart grids, energy storage, and cleaner industrial production technologies.*
- *Enact holistic zoning policies at the local level that promote greater population and employment densities, more compact urban forms, accessible and adequate green space, and public and non-motorised mobility options.*

The world's energy future is inextricably linked to its urban areas. High urban concentrations of people and economic capital, and the characteristics of urban buildings, transport systems, industrial processes and energy infrastructures, all heavily inf uence global energy use. As of 2015, 3.9 billion people were living in urban areas, representing 52% of the global population of 7.3 billion. By 2050, the world's urban population will reach 6.3 billion, or two-thirds of the projected global population of 9.5 billion (UN DESA, 2014a).

Urban population growth will continue to place pressure on national and local governments not only to deliver basic services such as energy access, affordable housing, public health, disaster risk management and economic development, but to do so in a way that meets sustainable energy goals.

This introductory chapter outlines the rationale for prioritising urban energy systems in *Energy Technology Perspectives 2016* (*ETP 2016*). It summarises the major components and drivers of energy use by the world's urban areas, and presents the results of *ETP* scenarios for global urban energy use and CO_2 emissions. It stresses the importance of national and local policy co-ordination, and provides examples of policy actions for enabling transitions to sustainable urban energy systems.

In *ETP 2016*, sustainable urban energy systems are broadly defined as meeting demand for urban energy services while 1) protecting the environment (including mitigating climate change, reducing air pollution and avoiding natural resource depletion); 2) improving the resilience of urban energy infrastructure to external shocks; and 3) achieving economic and human development goals.

A transition to sustainable urban energy systems will require deploying a mix of clean energy technologies while also changing the behaviour of energy users, for example through greater use of public transport. Sustainable options exist at every level of the urban energy system, from primary energy production through transformation to consumption.

In addition, the density and diversity of energy demand in urban areas offers valuable opportunities for integrating different energy networks, such as electricity, heat and buildings. Opportunities for system integration can arise from options such as smart grids and distributed storage. District heating and cooling (DHC) networks can also be a source of flexibility for accommodating variable renewable energy sources, such as wind and solar power, and excess heat (e.g. from industrial processes or municipal waste water treatment).

Municipalities often have jurisdiction over such core determinants of energy use as zoning and building codes, business licensing, transport planning and, in many cases, local power distribution networks. However, national governments can provide much greater support through investments in RD&D of clean energy technologies, development of energy efficiency standards, facilitating co-ordination among national, subnational and local agencies and their planning and energy policies, and other national policy actions described in *ETP 2016*. Strong private-sector engagement is also critical for the clean energy transition.

Some national governments have already begun creating policy frameworks that empower cities to make the transition to sustainable energy systems. Governments can expand this support in many ways, including by formulating national urban energy plans and developing or making available urban energy planning tools that advance local and national clean energy goals.

ETP 2016 identifies a diversity of cost-effective technologies and strong policy actions that can make urban energy systems more sustainable. It presents urban analysis within the 2°C Scenario (2DS) that can help cities and countries assess what is possible and realistic in their own contexts, and in terms of the energy performance and costs of different technology pathways. Each chapter focuses on the challenges and opportunities related to a major urban energy system component:

- Rapid urban growth presents both challenges and opportunities for energy-efficient residential and commercial building stocks, including new building energy standards and deep energy renovations of existing buildings, especially in developing countries. Cities can use a combination of national and local policies to reduce building energy demand significantly and avoid "locking in" inefficient urban built environments (Chapter 4).
- Growing demand for urban mobility brings significant opportunities to avoid unnecessary travel, shift activity to public transport and support the spread of more efficient low-carbon vehicles. Local and national policy makers can implement a broad portfolio of measures to realise this transition (Chapter 5).
- Urban energy supply systems can be made sustainable by use of cleaner energy sources and by investing in infrastructure to deliver cleaner and more secure electricity, heat and fuels, and to maximise integration opportunities using smart grids (Chapter 6).

- Integrating local and national policy making can enable planning approaches and policy instruments that support technology adoption and promote behavioural change that increases energy efficiency and renewable energy use in cities (Chapter 7).

Additionally, as in previous editions, *ETP 2016* recognises the importance of emerging economies in the energy transition by including a focused review of one of the International Energy Agency (IEA) accession countries:

- Ambitious goals and targets define Mexico's plans to transition to cleaner urban energy systems, demonstrating how emerging economies can link energy technology innovation and energy policy with their economic growth objectives (Chapter 8).

Why urban energy systems?

Urban areas[1] account for the greatest shares of both global population and world economic activity, which are two key drivers of societal energy use. As such, the world's urban areas have substantial influence over global energy demand and energy-related environmental emissions. This influence will continue to strengthen as populations and economies continue to grow and urbanise.

In addition to meeting growing demand for urban energy, many governments face the challenges of providing clean energy access and reducing exposure to harmful air pollution. A transition to more sustainable energy systems can not only meet these challenges but also deliver additional benefits, for example by increasing energy security, improving resilience and fostering innovation. The following subsections discuss each of these factors to underscore the importance of sustainable urban energy systems as a pressing policy priority, for both national and local governments.

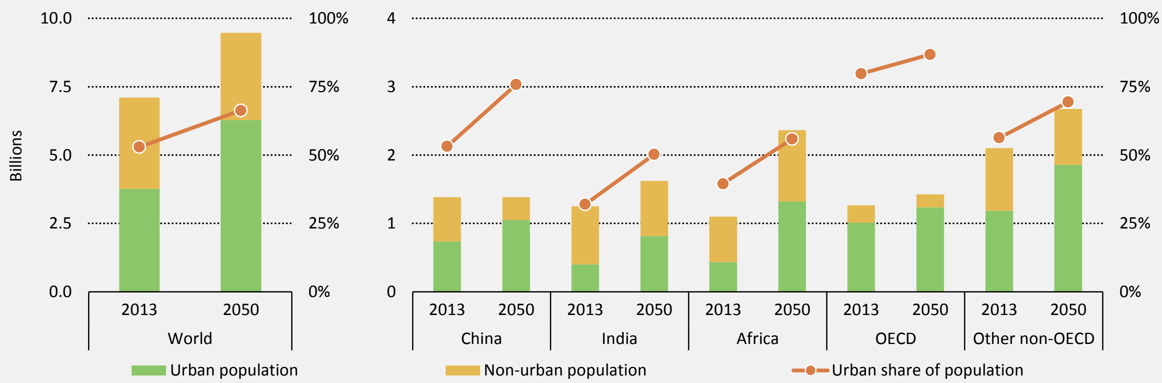
Urban populations are rising

Much of the population growth projected by 2050 will occur in developing economies, particularly in India, Africa and non-Organisation for Economic Co-operation and Development (OECD) economies in other regions (Figure 3.1). This growth, combined with continued economic development, will increase demand for energy services as both affluence and basic energy access levels rise. By contrast, only moderate population growth is expected in OECD economies, where per capita demand for energy services is substantially higher, but is also generally stable due to higher market diffusion of end-use technologies (e.g., appliances and personal vehicles) and the growing effects of energy efficiency policies such as building energy codes and appliance standards.

In all world regions, urbanisation is expected to continue to 2050. In OECD economies, the urban population is expected to rise from 80% of total population in 2013 to 87% by 2050. China will also become highly urbanised, with 76% of its population living in cities by 2050, compared with 53% in 2013. Pronounced population shifts will also occur in India, where the urban population will rise from 33% in 2013 to 50% in 2050, and in Africa (from 39% to 55%). By 2050, the urban populations in India, China and Africa will account for roughly one-third of the world's population. Large urban populations combined with rapidly developing per capita demand for energy services will make the transition to sustainable urban energy systems particularly important in these economies.

1 In *ETP 2016*, urban areas are not defined explicitly in terms of consistent settlement characteristics, population thresholds, or population density thresholds across *ETP* model regions. Rather, urban energy use and CO_2 emissions are estimated for each *ETP* model region on the basis of external datasets for urban population and urban economic activity (as described later in this chapter), along with further assumptions related to urban energy technology characteristics and energy service demand drivers (as described in Chapters 4, 5 and 6).

Figure 3.1 Projected urban and non-urban population, global and regional, 2013-50



Note: Figures and data that appear in this report can be downloaded from www.iea.org/etp2016.
Source: UN DESA(2014a). *World Urbanization Prospects: The 2014 Revision*, http://esa.un.org/unpd/wup/.

Key point *By 2050, two-thirds of the world's population will live in urban areas, with the greatest growth in China, India, Africa and non-OECD economies in other regions.*

Most urban growth will occur in small cities, with populations of less than 500 000, and medium-sized cities of less than 1 million people (UN DESA, 2014b). In such cities, the resources and capacities for implementing effective urban energy policies are typically much weaker than those in large cities (Grubler et al., 2012). Strong co-ordination between national and local policy makers will therefore be particularly important in these small to mid-sized cities to ensure comprehensive policy design and deployment, sharing of best practices, and the necessary investments in sustainable and ef cient urban energy systems and technologies.

Rapid urbanisation in developing countries is also likely to increase the land occupied by cities, given that many of these cities are expanding in uncontrolled ways to meet the needs of swelling populations. Without action to limit rapid, sprawled expansion of the urban built environment, more land may be required to meet growing urban populations from 2000 to 2030 than has been required for urban areas in all of human history to date (Lucon et al., 2014).

Urban economies are growing rapidly

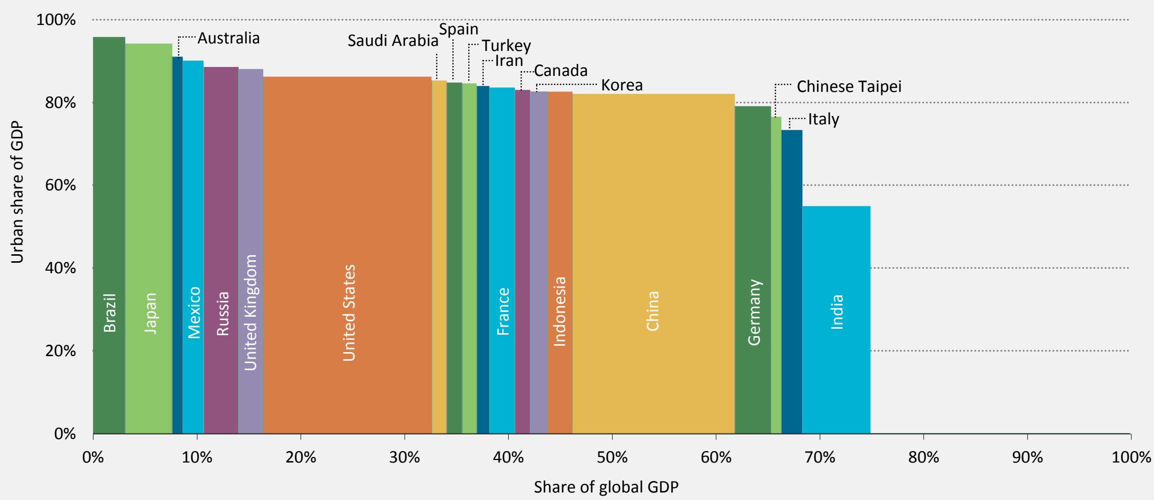
Urban economies account for the vast majority of global economic activity (expressed as GDP) and can be considered the world's economic engines. In 2013, urban areas generated an estimated GDP of USD 86 trillion,[2] which made up 82% of global GDP. In 2013, 19 of the world's 20 largest economies had an urban share of GDP of at least 70% (Figure 3.2). At the global level, urbanised economies are similarly dominant: three-quarters of total global GDP in 2013 occurred in 88 economies with urban GDP shares greater than 80%. Urban areas are, therefore, vital to national economic goals and competitiveness in most countries, which lends them high importance for national economic, social and energy policy focus.

As global economic development continues, urban GDP is expected to grow significantly (Figure 3.3). Between 2013 and 2050, global urban GDP is projected to more than triple from USD 86 trillion to USD 285 trillion. Over the same time period, the urban share of

2 Unless specified differently, USD figures are in purchasing power parity (PPP) in constant 2014 terms.

global GDP is projected to rise from 82% to 84%, which suggests that urban areas will continue to dominate the world economy. The greatest growth in urban GDP is expected in China, India, Africa and non-OECD economies in other regions.

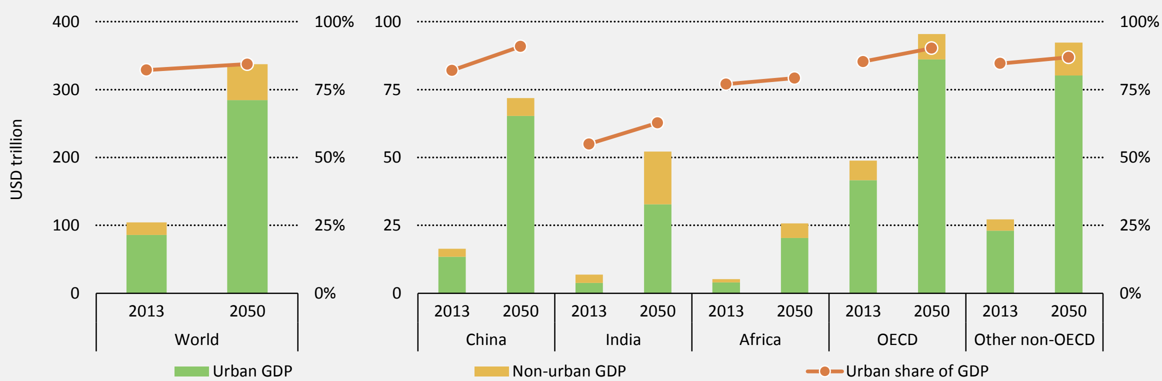
Figure 3.2 Urban contributions to GDP, 20 largest economies, 2013



Source: IEA analysis derived from McKinsey (2015), *McKinsey Global Institute Cityscope* v2.55; IMF (2015), *World Economic Outlook Database*, www.imf.org/external/pubs/ft/weo/2015/01/weodata/index.aspx; IEA (2015a), *World Energy Outlook 2015*.

Key point *The world's largest economies are highly urbanised.*

Figure 3.3 Projected urban and non-urban GDP, global and regional, 2013-50



Sources: IEA analysis derived from McKinsey (2015), *McKinsey Global Institute Cityscope* v2.55; IMF (2015), *World Economic Outlook Database*, www.imf.org/external/pubs/ft/weo/2015/01/weodata/index.aspx; IEA (2015a), *World Energy Outlook*.

Key point *Urban areas will account for the vast majority of global GDP growth to 2050.*

The dominance and growth of urban GDP have at least two important implications for global energy demand. First, economic activity is typically strongly correlated with demand for energy services, which accords the world's urban areas significant influence on current and future global energy demand. The energy intensity of an urban economy is dependent upon both its economic structure (i.e. the contributions of the services, industry, transport and other economic sectors) and the energy efficiencies of its economic sectors. As such, the effects of urban GDP growth on global energy demand will largely be determined by how the economic structures and energy efficiencies of urban areas evolve and are shaped by national and local energy policies.

Second, growth in urban GDP will also increase the prosperity of urban inhabitants, which historically has led to higher per capita consumption of goods and services and greater ownership of energy-using equipment and personal vehicles (Lucon et al., 2014). The potential for higher per capita consumption will augment the pressure on national and local governments to ensure sustainable urban energy transitions while meeting growing demand for energy services.

The majority of urban GDP growth will occur in developing and emerging economies. This growth may be explained, in part, by shifts away from rural and agricultural economies to those based more on services and manufacturing located in or around cities. By 2050, 70% of projected urban GDP – USD 199 trillion – will be generated by urban areas in China, India, Africa and non-OECD economies in other regions. Sustainable urban energy transitions will be critically important in these economies, where rapid urban GDP growth will create both opportunities and challenges for national and local governments in the transition to sustainable urban energy systems. As urban GDP grows, governments can direct technology investments, enact policies and pursue urban plans that "lock in" pathways toward more sustainable and efficient urban systems. Conversely, inaction during periods of rapid urban economic growth and development may lead to the undesirable outcome of "locking in" inefficient urban plans, built environments and energy systems for years to come.

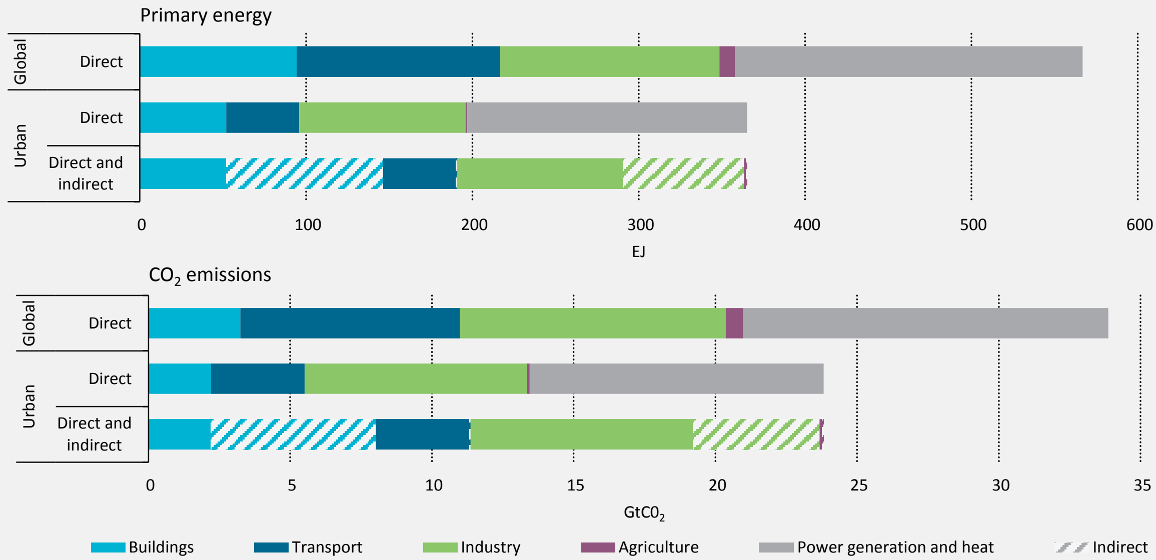
Urban areas dominate global energy use

Given their high concentrations of population and economic activity, the world's urban areas play a dominant role in global energy use. *ETP 2016* analysis estimates that the world's urban areas accounted for 365 EJ of primary energy use in 2013, or 64% of global primary energy use (Figure 3.4). From a sectoral perspective, direct fuel use by the power sector (for electricity and heat generation) accounted for the largest share of urban primary energy use, followed by direct fuel use by the buildings (residential and services combined), industry and transport sectors within urban areas. When direct fuel use by the power sector is distributed to end-use sectors on the basis of their consumption of electricity and heat, the buildings and industry sectors emerge as the largest total (direct plus indirect) contributors to urban primary energy use, followed by the transport sector.

CO_2 emissions attributable to the world's urban areas in 2013 are estimated at 23.8 Gt, or 70% of the global total. As for primary energy use, when power-sector emissions are distributed to end-use sectors on the basis of their use of electricity and heat, the buildings and industry sectors are the largest total (direct plus indirect) contributors to the CO_2 emissions of the world's urban areas, followed by the transport sector. The contributions of the agriculture sector to global urban primary energy use and CO_2 emissions are expected to be small.[3]

3 IEA analysis of economic datasets from McKinsey (2015) and IMF (2015) suggests that, globally, less than 15% of economic activity in the agriculture sector currently occurs in urban areas.

Figure 3.4 Global urban primary energy use and CO_2 emissions, 2013



Note: Direct emissions for industry include 1.9 $GtCO_2$ of process-related emissions in the global total and 1.3 $GtCO_2$ in the urban total.

Key point *The world's urban areas account for the majority of global primary energy use and CO_2 emissions.*

ETP 2016 derives its estimates of urban energy use and CO_2 emissions in a manner that is broadly consistent with the production (or territorial) energy accounting approach for each *ETP* model region (Grubler et al., 2012). For the buildings sector, urban final energy demand was estimated using assumptions for the total residential f oor area and number of households in urban areas (for the residential subsector), the total commercial f oor area in urban areas (for the services subsector), and further assumptions on the energy use characteristics of urban buildings within each subsector (see Chapter 4). For the transport sector, urban final energy demand was estimated using assumptions for passenger and freight modal shares, activity levels, and technology characteristics within urban areas (see Chapter 5). For the industry and agriculture sectors, urban final energy demand was estimated by multiplying total sectoral final energy demand (see Chapter 1) by the ratio of urban value added to total value added for each sector.[4] This approach assumes that urban economic activity is a proxy for geographical location within each *ETP* model region (Box 3.1), which results in large shares of industrial energy use and emissions attributed to urban areas in countries and regions with substantially urbanised industrial economic activity (including China, the United States, the European Union, Brazil, Russia and India). For the power sector, urban fuel inputs were estimated based on the heat and electricity requirements within the urban final energy demand of each end-use sector.

4 The estimation of urban added value for agriculture and industry for 189 economies from 2013 to 2050 was based on data from the *Oxford Economics Global City* database, IEA urban GDP estimates, and regional growth rates from the IEA *World Energy Outlook 2015* (IEA, 2015a). Data from the *Oxford Economics Global City* database, covering 770 cities and metropolitan areas and accounting for an estimated 65% of global urban GDP, were used to estimate national ratios of urban industry added value to urban total added value from 2013 to 2030. Projections from 2030 to 2050 were developed using the regional agriculture and industry added value growth rates from the IEA *World Energy Outlook 2015*.

More detailed estimates of global urban energy use and emissions are complicated by a lack of urban-scale energy and emissions statistics in most countries. Where urban-scale datasets and reports exist, differences in energy accounting approaches, urban geographical boundary definitions, temporal coverage and sample sizes can often preclude direct comparability for deriving global estimates. Despite inherent uncertainties, the *ETP 2016* estimates highlight the dominant role that urban areas play in current global energy use, and reinforce the message that the nature and scale of energy use by urban areas will heavily influence the world's energy and CO_2 emissions trajectories in the future.[5] Therefore, strong, near-term policy actions are required by national and local governments to enable and accelerate sustainable urban energy system transitions.

Box 3.1 How much industrial energy use is urban?

The industry sector accounted for about 40% of global final energy demand (including feedstocks) and 25% of global direct energy-related CO_2 emissions in 2013. Therefore, the extent to which industrial energy use is included in urban-scale estimates can have a major influence on results in many countries.

Geospatial data on the energy use of industrial plants are rare. While plant locations are sometimes known, associated data on fuel inputs are typically not publicly available. However, plant-level air emissions data may offer useful insights in countries where such data are available, such as the United States (US EPA, 2015a, 2015b) and Canada (Environment Canada, 2015). For example, the geographical distribution of energy-related air emissions might be used as a proxy for the geographical distribution of on-site industrial fuel use within a country.

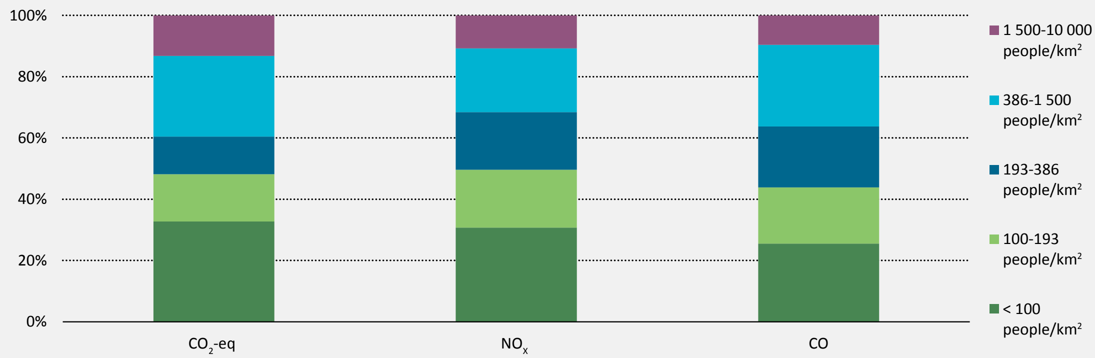
As an example, the US Environmental Protection Agency's Greenhouse Gas Emissions from Large Facilities Database and National Emissions Inventory provide annual reported data on energy-related emissions for thousands of US industrial plants. Of the annual emissions of CO_2, carbon monoxide (CO) and nitrogen oxides (NO_x) reported, around two-thirds of the total mass of each pollutant was released in a metropolitan county, which is defined as one containing a core urban area of 50 000 or more population (US Census, 2015). Within US metropolitan counties, however, population density variations can exist in the areas surrounding the reporting plant (Figure 3.5).

These data highlight that how an urban area is defined can significantly affect the share of industrial energy use attributed to urban areas. In the US example, choosing a population density threshold associated with an "urban cluster" or an "urbanised area" would lead to smaller fractions of industrial energy use and emissions assigned to urban areas at the national level compared with using the US metropolitan county definition of urban areas. Roughly one-half of US metropolitan county emissions fall below the "urban cluster" threshold, while roughly two-thirds fall below the "urbanised area" threshold.

Because plant-specific emissions data are not yet reported across the many global regions considered in the *ETP 2016* analysis, urban value added is used as a proxy for urban industrial plant locations. If plant-level data emerge for additional countries in the future, the accuracy of global urban industrial energy use and emissions estimates can improve accordingly.

5 This message is consistent with those of previous studies. In 2012, the *Global Energy Assessment* took a production approach using urban energy models complemented with geographical information systems data to estimate that 60-80% of global final energy use is attributable to urban areas (Grubler et al., 2012). In 2008, the IEA *World Energy Outlook* used a production approach based on global energy models and city-level data from a sample of key global cities to estimate that urban areas account for 67% of global final energy use (IEA, 2008).

Figure 3.5 **Share of US metropolitan county industrial plant CO_2-eq, NO_X and CO emissions by population density**



Note: Based on 1 625 reporting plants for CO_2 emissions in 2014, 8 890 plants reporting NO_x emissions in 2011, and 8 628 plants reporting CO emissions in 2011. Urban cluster and urbanised area density thresholds based on US Census (2000).
Source: US EPA (2015a, 2015b).

Key point *Industrial emissions in US metropolitan counties span a large population density range.*

Sustainable urban energy systems help protect human health

In many of the world's cities, there are two pressing human health challenges: energy poverty and air pollution. Transitions to sustainable urban energy systems can simultaneously address both of these challenges by providing widespread, reliable access to cleaner and more ef cient energy systems.

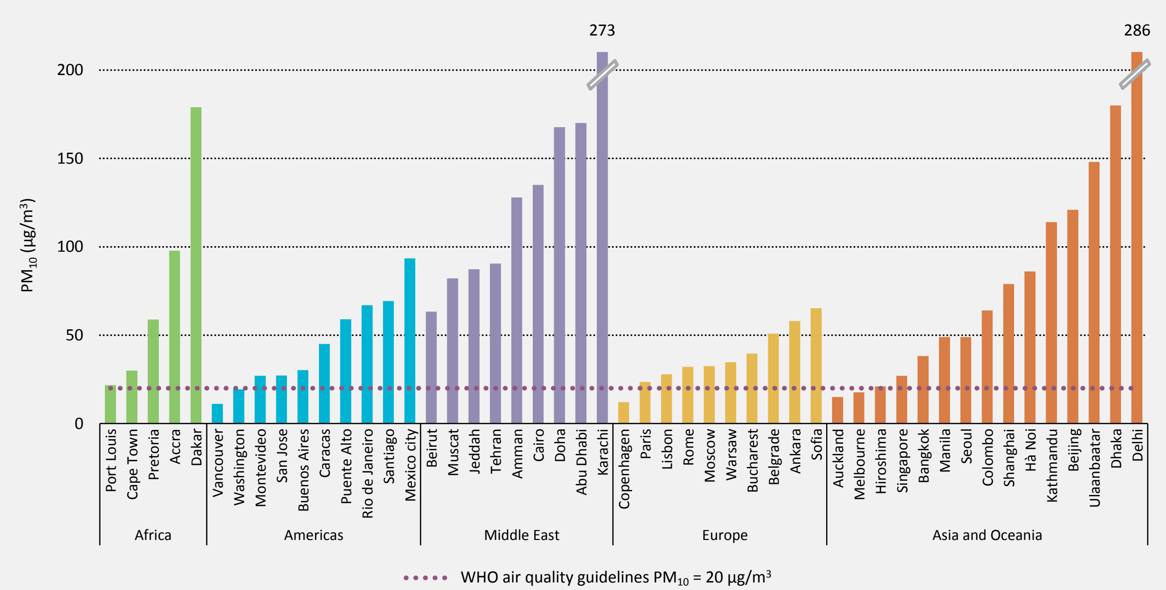
Energy poverty refers to lack of access to affordable, reliable and clean sources of energy, particularly for cooking and heating (IEA, 2010; IEA 2011). Traditional use of biomass (e.g. wood, charcoal and dung) dominates cooking and heating in many developing world cities, particularly in Sub-Saharan Africa. Energy poverty is widespread in cities, with around 800 million of today's 3.9 billion urban inhabitants (20%) living in poor conditions with inadequate access to basic energy services, predominantly in low- and middle-income countries (Grubler et al., 2012). Even when cleaner commercial fuels are available, many urban poor still struggle to pay for them.

Traditional use of biomass is also a leading cause of ill health from indoor air pollution worldwide. The World Health Organization (WHO) estimates that in 2012, 4.3 million deaths were attributable to household air pollution (WHO, 2014a). Almost all of these deaths were in low- and middle-income countries, and the vast majority were in Southeast Asia and the Western Pacific.[6] Providing affordable, reliable urban access to cleaner commercial fuels for heating and cooking, including low-carbon electricity and natural gas, must therefore be a policy priority for many low- and middle-income countries as a means of alleviating energy poverty, protecting human health and lifting urban dwellers out of poverty.

6 The WHO's Southeast Asia region includes Bangladesh, Bhutan, Democratic People's Republic of Korea, India, Indonesia, Maldives, Myanmar, Nepal, Sri Lanka, Thailand, Timor-Leste. The WHO's Western Pacific region includes Australia, Japan, New Zealand, Republic of Korea, Singapore, China and Viet Nam.

Ambient (outdoor) air pollution is an equally severe health issue in many urban areas, across high-, middle- and low-income countries. Ambient air pollution typically arises from fuel combustion in vehicles, power plants, buildings and industrial plants and is worse in congested areas with smog-prone climates and geographies. According to the WHO, 88% of people in cities that report on air quality are exposed to air pollution levels that exceed WHO air quality guidelines (WHO, 2014b).[7] Furthermore, about half of the inhabitants are exposed to particulate matter (PM) levels at least 2.5 times higher than the WHO guidelines (Figure 3.6) (Box 3.2).

Figure 3.6 PM_{10} levels for selected cities by region, 2008-12



Note: Data are from last available year for each city during the period 2008-12.
Source: Reprinted with permission from WHO (2014c).

Key point *In many cities, air pollution levels signif cantly exceed WHO air quality guidelines.*

Globally, 3.7 million deaths were attributable to ambient air pollution in 2012 (WHO, 2014b). About 88% of these deaths occurred in low- and middle-income countries, with 70% occurring in the Western Pacific and Southeast Asian regions where urban populations are poised to grow significantly. Transitions to cleaner urban energy systems, particularly in these two developing regions, would significantly reduce the health burden of outdoor air pollution. Relevant policies and investments include supporting cleaner transport, energy-ef cient housing, clean power generation, industrial energy ef ciency and fuel switching, and better municipal waste management to reduce emissions from incineration.

Sustainable urban energy systems bring multiple benefits

Given their high concentrations of people and economic activity and their inf uence on national energy systems, urban areas play a key role in helping countries meet their goals for energy technology innovation, energy security and infrastructure resilience. Policies and technology investments that promote sustainable urban energy systems should therefore be priorities for local and national policy makers.

7 WHO $PM_{2.5}$ guideline = 10 micrograms per cubic metre (µg/m^3) annual mean; WHO PM_{10} guideline = 20 µg/m^3 annual mean.

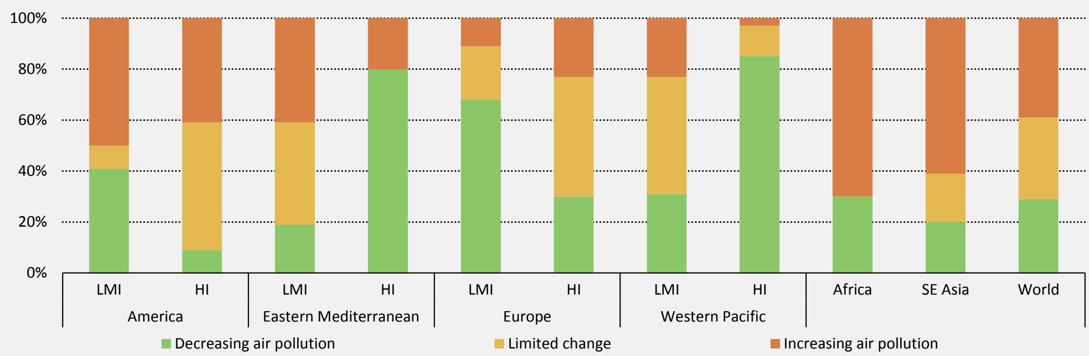
Box 3.2 Is urban air pollution getting better or worse?

The WHO maintains an air quality database that covers 1 600 cities in 91 countries for assessing human exposure based on data from monitoring stations, national and regional agencies, and other credible sources. These data provide a unique resource for establishing air quality trends in the world's cities, using ambient levels of PM_{10} and $PM_{2.5}$ as key indicators (WHO, 2014d).

WHO findings for cities for which there are sufficient data to compare present and past levels of ambient PM_{10} show that for most people, air pollution is steady or getting worse, across developed and developing regions alike (Figure 3.7).

The WHO attributes these findings to many factors, including reliance on coal-fired power plants, dependence on private vehicles, inefficient use of energy in buildings, and the traditional use of biomass for cooking and heating. Despite the overall global trends of stable or deteriorating air quality in cities, significant progress has been made in some cities within every region, through policy measures such as banning the use of coal for space heating in buildings, using renewable or clean fuels for electricity production, and improving efficiency of vehicle engines (WHO, 2014c).

Figure 3.7 Percentage of city population experiencing increasing and decreasing PM_{10} annual means by region



Notes: LMI: Low- and middle-income; HI: high-income; SE: Southeast; limited change refers to changes of less than +/-3% per year. Regions correspond to WHO definitions.
Source: Reprinted with permission from WHO (2014c).

Key point *Ambient air quality is not improving, or is getting worse, in many of the world's cities.*

Fostering innovation

There are numerous examples of cities serving as living laboratories for clean energy technologies and related polices, where successful demonstrations can lead to broad replication within and beyond national boundaries (C40, 2015). Such demonstrations can be critical for improving technology performance, reducing perceived risk, testing policy instruments and encouraging additional investments – especially for early-stage or disruptive technologies, which often have dif culty making the leap from R&D to market deployment (IEA, 2015b). For example, the *EV City Casebook* documents many leading-edge examples of policies and strategies aimed at increasing urban use of electric vehicles (EVs) to meet local and national clean energy goals, including measures aimed at changing personal transport preferences (Urban Foresight, 2014).

Urban pilots and demonstrations also provide opportunities for cities to engage in public-private partnerships, in which businesses provide and test their technologies, defraying investment costs for local and national governments. These partnerships are good for both cities and businesses, as they can stimulate the local economy, create jobs and offer valuable "real world" test beds to companies for further technology improvements (Box 3.3).

Box 3.3 Yokohama Smart City Project

In Yokohama, the second-largest city in Japan (population 3.7 million), rapid urbanisation has increased energy use, traffic jams, pollution and greenhouse gas (GHG) emissions. The Yokohama Smart City Project (YSCP) strives to improve management of energy use and mitigate climate change.

YSCP began as a five-year pilot in three city districts in 2010 with support from Japan's Ministry of Economy, Trade and Industry as part of Japan's Smart City programme. It has since been deployed to the entire city, covering about 435 square kilometres. The project uses smart grids to manage the energy needs of households, buildings and local communities; introduces large-scale renewable energy; and promotes next-generation transport systems to demonstrate new urban management forms.

The city introduced a Community Energy Management System (CEMS) to achieve efficient energy management by linking individual emergency management systems (EMS), such as in homes and buildings, factories, and stationary energy storage. Specific achievements included:

- EMS in 4 200 homes
- Introducing 2 300 electric vehicles
- Introducing 37 MW of photovoltaic generation
- 39 000 tonnes of CO_2 emissions reduction.

In addition, solar power generation will be implemented in 265 locations, wind in two locations, hydropower in four, and biomass power generation in six locations. Consumers will receive incentives to limit electricity use, thus reducing CO_2 emissions at a lower social cost.

CEMS is based on a public-private partnership between Yokohama City and 34 technology, energy and management companies. These innovative collaborations aim to provide businesses with large-scale opportunities to demonstrate and improve technology. They also aim to increase the competitiveness of Japanese industry, spur innovation and job creation, and help Yokohama City to reach its goals of reducing CO_2 emissions by 16% by 2020, by 24% by 2030 and by 80% by 2050 (compared with 2005 levels).

Citizen participation is a key component of the YSCP. For example, the Yokohama Eco School project was developed to increase citizen participation in YSCP and educate citizens about climate change through lectures, events and workshops. In 2014, 377 lectures were held for 35 000 participants and 142 partner organisations. This led to an increased number of EMS, photovoltaic (PV) generation systems and storage batteries installed in homes. Additionally, 4 000 households participated in the fiscal year 2014 demonstration project, showing a high level of engagement and making YSCP one of Japan's largest energy-saving projects. The project encourages citizens to be more environmentally aware by introducing EVs, reducing ambient air pollution and promoting healthy lifestyles (City of Yokohama, 2014).

Enabling energy security and resilience

Given urban predominance in national energy demand, economic activity and concentration of infrastructure in many countries, many cities can be key enablers of improved national energy security and resilience. The IEA defines energy security as the uninterrupted availability of energy sources at an affordable price. Achieving energy security requires the energy sector to be resilient to a range of events or trends, including changing climatic conditions, price shocks and geopolitical events. Resilience refers to the capacity of the energy system or its components to cope with such changes and to respond in ways that maintain its essential function, identity and structure. Lack of energy security can increase the risk of supply disruptions as well as exposure to energy price volatility. The repercussions for urban areas can be numerous, including loss of heating and cooling for buildings, loss of critical health and public safety services such as water treatment and emergency services, interruption of mobile communication, reduction in mobility, and the costly addition of peak generation capacity.

ETP 2016 discusses a range of clean energy technologies and policies that can enable greater energy security through such strategies as greater use of local energy sources, integration of smart grids for optimising supply-and-demand relationships, DHC systems to reduce fuel inputs, and reducing energy demand pressures through more ef cient buildings and transportation systems. Implementation of these measures can not only help decarbonise energy systems but also build resilience (Box 3.4). For instance, reducing total and peak energy demand can limit the exposure of energy users to supply interruptions, decentralising energy sources can improve the ability to buffer and localise outages, and developing local energy sources can reduce exposure to fuel supply interruptions caused by international geopolitical conf icts.

Box 3.4

Resilience in urban energy systems

As the global energy sector begins to register the effects of climate change, urban areas are on the front lines – not only in feeling these impacts but also in responding to them. The World Bank estimates that over 80% of global costs for climate change adaptation from 2010 to 2050 could be carried by urban areas (World Bank, 2011).

Climate change has many different effects on urban energy systems. Extreme weather events pose risks to buildings and transport systems and electricity infrastructure, especially transmission and distribution systems. Many urban centres are on or near coastlines, and face direct risks from rising sea levels and flooding (Hanson et al., 2011). Changes in water availability, coupled with a rising demand for water, can constrain hydropower, bioenergy (particularly irrigation-dependent biofuel production) and the operation of thermal power plants (fossil fuel and nuclear), which require water for cooling. Variable renewable energy sources such as solar and wind power can be affected by changes in cloud cover, wind speed and wind direction, as well as extreme weather events. These impacts on the energy supply chain, including fuel extraction and processing, may not take place within urban centres but can be felt through fuel price volatility and interruptions in fuel availability within cities.

Climate change may also affect energy demand; increased ambient air temperatures may be further exacerbated in urban areas by heat island effects. This may increase energy demand for space cooling, and corresponding higher peak loads may require additional generation capacity.

A range of local policy responses can help enhance energy resilience in the face of climate change. These include strengthening emergency response measures in the event of extreme weather events, upgrading building codes and zoning by-laws (e.g. prohibiting building in high-flood-risk areas), and building in redundant power capacity. Measures such as enhancing energy efficiency and demand-side management, diversifying the energy mix and decentralising energy generation can not only build resilience but also help achieve sustainable urban energy system objectives.

A sound approach to enhancing energy sector resilience will also include measures to mitigate other risks, such as cyberattacks, market fluctuations, political and social instability, and conflict.

Understanding urban energy systems

Urban areas differ widely in terms of their population, population density, vintage, economic activities and growth rates, climate and land use, but all depend on energy for the various activities that take place within them. Urban areas themselves are systems of interconnected networks and components, and the ways they produce and use energy is also a system – an urban energy system.

It is necessary to understand the components of urban energy systems to identify possible interactions between them. Breaking down an urban energy system into its components also allows for the classification of urban energy systems into different types, and is the first step to analysing drivers for energy use within a particular urban area or city.

The type of urban energy system determines available opportunities for policy makers to create a *sustainable* urban energy system; certain factors, notably urban population density, have a significant influence over those opportunities. *ETP 2016* focuses on certain major opportunities and policies that can work in most cases and address the greatest energy sustainability opportunities: efficient buildings and urban forms, efficient industrial processes, public and non-motorised transport systems, renewable energy sources and energy integration (Figure 3.8).[8]

Components of urban energy systems

While there are many ways of defining the components of urban energy systems, in *ETP 2016* they are defined broadly as buildings (comprised of residential and services buildings), transport (comprised of passenger and freight transport), heat and power, industry, water treatment, waste treatment and agriculture (Table 3.1). The characteristics of these components can further vary based on their specific locations within an urban geographical area, ranging from high-density urban cores to lower-density peri-urban areas.

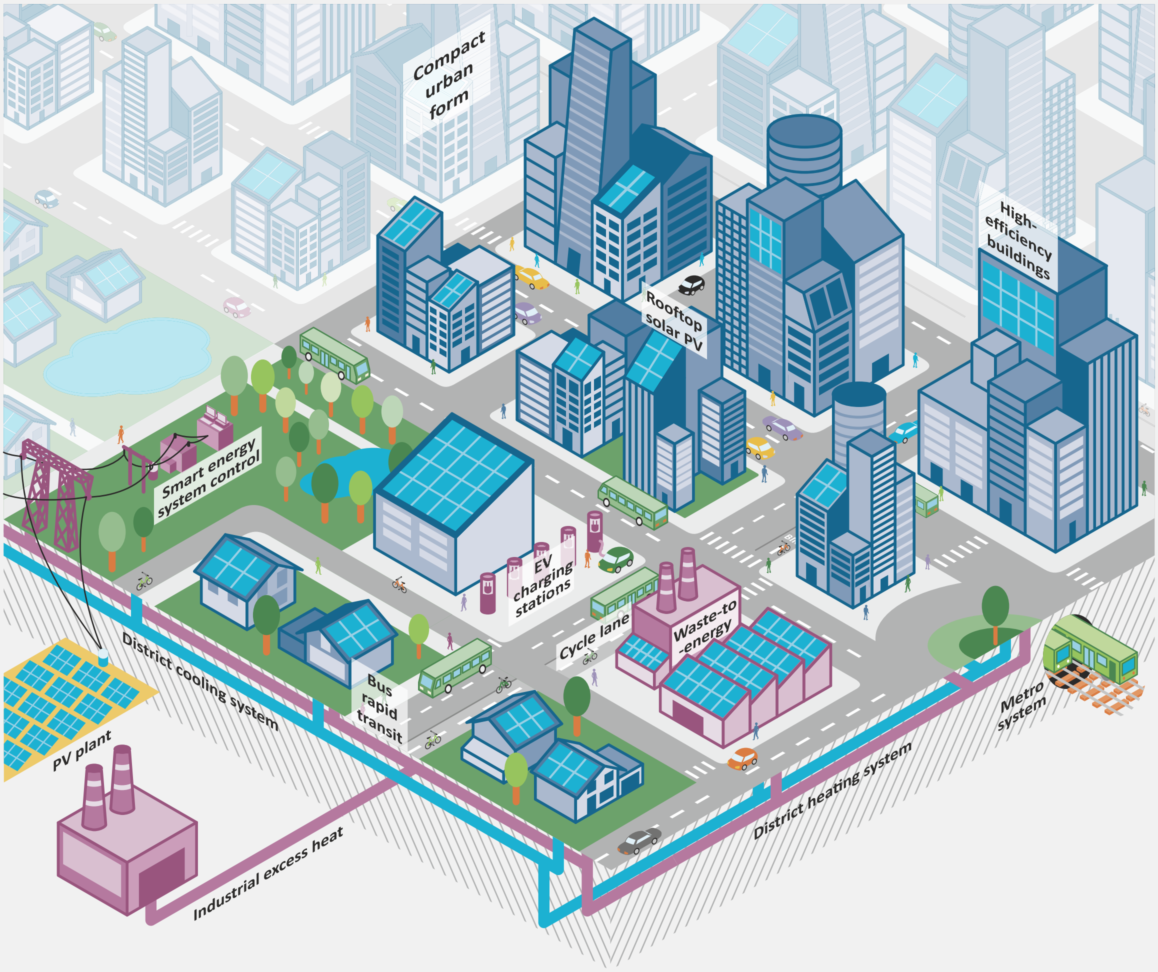
The components of an urban energy system are structured differently and interact in different ways depending on how the system has developed. In many newer cities in developed countries, for example, these components have often been designed to integrate with one another according to a pre-defined urban plan. In contrast, there may be little integration between energy system components in mature cities of developed economies (particularly those that developed before the advent of urban planning), and in rapidly urbanising developing economies, where planning laws are often non-existent or contravened.

Beyond the influence of an urban planning regime, certain key factors affect how urban energy systems develop:

- **Affluence**: The level of affluence (which can be defined as GDP per capita) within a city can affect the energy system in several ways. First, energy use tends to be higher in more affluent cities, where residents use their economic power to purchase more goods and services, which often leads to higher energy use. Second, the level of affluence may affect the costs associated with major energy system investments. For example, the cost of land acquisition for building or expanding a public transport system in a highly affluent city may be prohibitively high, posing challenges for project financing. Third, the level of affluence can also affect the availability of human and economic capital available for making and managing sustainable energy technology investments.

8 Sustainable energy transitions for the industry sector are discussed at the global level in Chapter 1.

Figure 3.8 Key elements of sustainable urban energy systems



Key point *Compact urban forms, efficient buildings and transport systems, and low-carbon, integrated energy networks all play a role in sustainable urban energy systems.*

- **Density**: The population density of an urban area (generally defined as number of people per square kilometre) is a major determinant of how energy system components develop. For example, urban areas with high density may meet demand for housing by building high-rise residential buildings. In densely populated cities with high demand for transport, capital-intensive public transport options such as metro systems are also more economically viable. Contrastingly, low density urban areas tend to contain lower-rise building stocks and public transport options with lower capital costs such as buses.
- **Building stock and infrastructure age**: In well-established cities, such as in many parts of Europe, the building stock may be older, often because of the desire to preserve historical buildings' heritage value. This can lead to higher energy use, as such buildings were not designed with modern energy uses in mind. This also affects the non-building components of the urban energy system: the deployment of modern electricity, water and heat networks may be limited by the need to service older buildings with outdated facilities. In contrast,

new buildings can be designed to incorporate energy-efficient technologies and to be more compatible with modern energy and water networks. Similarly, the age of the transport infrastructure can influence transport sector energy use. For example, outdated roadway systems can lead to vehicle congestion, sub-optimal passenger and freight logistics, and greater fuel use due to poor road surface conditions.

Table 3.1 Energy system components in urban, suburban and rural areas

Sector	Urban core (high to medium density)	Suburban (medium to low density)	Rural (low density)
Residential buildings	Mostly densely clustered multi-family dwellings; lower per-capita floor area; higher consumption of goods and services in developed economies.	Large clusters of mixed multi- and single-family dwellings; higher per-capita floor area; greater land use per dwelling.	Single-family dwellings in small clusters, higher per-capita floor area; greater land use per dwelling.
Service buildings	Mixture of high-rise and low-rise commercial buildings, with full range of private and public sector services.	Predominantly low-rise commercial buildings in large and small clusters; greater presence of direct-to-consumer (DTC) private sector services (retail, etc.).	Few low-rise buildings often clustered in town centres; primarily DTC and small public sector buildings.
Passenger transport	Mixture of private passenger vehicles, public subways, light rail, bus rapid transit and conventional buses, and pedestrian and bikeways.	Subways give way to light commuter rail, buses, and greater share of private passenger vehicles; airports on city peripheries; walking and biking less common.	Private transport dominated by passenger vehicles; intercity rail and bus lines occupy land.
Freight transport	Predominantly short-haul diesel trucks for delivery from agglomeration sites at urban periphery, which are fed by long-haul trucks, intercity rail, water and air.		Long-haul diesel trucks, heavy rail, water and air transport goods between urban centres and rural agglomeration points.
Heat and power	High demand densities provide opportunities for integrated heat, cooling and power systems with local generation; distributed renewable potential often limited by available land.	Lower density suburban areas less attractive to integrated heat and power systems; lower demand density and higher land availability make distributed renewables more viable.	Large centralised power systems face fewer land constraints, for both traditional and renewables, with long transmission distances to urban areas; opportunities for district heating and its generation option (CHP or heat plant) depend on local demand for heat by buildings and industry.
Industry	Locations of heavy and light industries vary widely across world regions depending on industry structure, demand and freight centres, settlement patterns, zoning ordinances, and local and national environmental regulations; mining operations predominantly rural due to large land use.		
Agriculture	Small-scale urban farms may augment food supply.		Larger-scale farms more common, using significant fractions of rural land areas.
Water	Drinking water and wastewater treatment plants located near population clusters; treatment scale proportional to populations served; greater opportunity for energy recovery in large scale operations.		
Waste	High-density collection networks with locations of separations (sorting, recycling) and disposal (incineration, waste to energy, landfill) facilities varying by city.		Low-density collection networks with longer transport distances to centralised separations and disposal locations.

- **Land availability**: In urban areas where land is plentiful and inexpensive, buildings and infrastructure are often spread out. For the energy system, this “urban sprawl” has historically led to higher energy use, as transport options were limited to inefficient modes, utility networks experienced greater losses, and residents inhabited more floor space per capita. However, urban areas with high land availability are sometimes best placed to benefit from modern distributed energy technologies, such as rooftop solar, having adequate space to deploy them.

- **Economic structure**: The economic activities within an urban area strongly affect the components and scale of the overall urban energy system. For example, urban economies dominated by the industry sector are generally more energy-intensive than those dominated by the services sector, and can further require different fuel supply mixes with different hourly energy demand profiles. Urban areas that serve as transport and freight hubs, such as port cities, may have significantly higher demand for transport fuels than those with predominantly industry or services sector economies. Urban areas dominated by services may require greater shares of electricity and natural gas in the supply mix to provide building energy services, often with much economic activity taking place in high-density buildings in a central business district.
- **Climate**: Climate directly affects the demand for heating and cooling services within an urban area, and can also have a significant impact on the way energy system components are integrated. For example, some cold climate cities utilise co-generation for integrated provision of electricity and district heat.[9]

These factors can provide a useful way to identify differences between urban energy systems, and for establishing different city "types" that help explain urban energy use patterns. For example, a hot-climate, low population density and affluent urban energy system is common in many Australian cities. The relationship between the type of urban energy system and energy usage patterns is not always clear and requires careful analysis. In developing countries, urbanites tend use more direct energy than rural inhabitants, while this relationship is typically reversed in developed countries (Grubler et al., 2012; Lucon et al., 2014).

Sustainable urban energy systems

No single model of urbanisation is necessarily best; just as urban areas have developed historically in different ways to form different "types" of energy systems, cities of the future will develop not only according to the factors outlined above but also depending on their different infrastructure starting points, social and cultural preferences, geography, and political and institutional capacity to plan and manage growth.

The transition to sustainable urban energy systems will therefore require different solutions for different contexts. New cities or expanding urban areas present the opportunity to plan urban energy systems so that components are integrated to achieve sustainability goals. In older cities, the high costs and limited possibilities of altering existing infrastructure may prohibit a fully integrated approach, but retrofits can help. Starting points for constructing sustainable urban energy systems can also be radically different; in the developing world, many urbanites still lack reliable access to electricity and clean water, especially in Southeast Asia and Sub-Saharan Africa.

Three urban energy system components have nevertheless been consistently identified as key "levers of urban sustainability" across world regions: buildings, transport, and heat and power. Specifically, dense and efficient building forms; public transport systems augmented with fewer but more efficient cars; and renewable energy, co-generation and waste heat capture and re-use (Grubler et al., 2012). Transitioning to more energy- and materials-efficient industrial systems, along with fuel switching and use of innovative processes – such as carbon capture and storage (CCS) – can be equally important sustainability "levers" in urban areas with significant industrial activity, such as in China.

It is tempting to think that that these solutions may only be appropriate in highly developed economies with many years of "technological learning". But recent experience has shown that rapidly growing cities can "leapfrog" to modern solutions, bypassing the intermediate steps that other cities have taken, in part because it is easier to adopt cutting-edge technologies in times of rapid transition, when change is frequent and acceptable. In contrast, the ability of

9 Co-generation refers to the combined production of heat and power.

some long-established cities in developed countries to adopt new technologies is inhibited by their long-term dependence on a particular development path.

Technological improvements are only part of the solution; systemic changes are often more effective for improving efficiency. For example, increasing the share of people taking public transport can save more energy than enhancing the efficiency of buses and trains, while ensuring that people in multi-tenant dwellings take public transport can save more energy than ensuring that families in the suburbs live in passive houses and drive hybrid cars (Grubler et al., 2012).

Drivers of urban energy use

Energy statistics tend to be collected at a national level. Understanding drivers of energy use at the urban level is much less developed, to a large degree due to the lack of data collection that can support comparisons across cities and countries.

Drivers of urban energy use can nevertheless be organised and analysed as follows:

- Drivers linked to the geophysical environment: The constraints imposed by a city's location, the prevailing climate conditions, or the resources at its disposal including proximity to other economic centres.
- Socio-demographic drivers: From the social and economic structure, to household occupation, to cultural aspects which drive the growth of a city.
- Drivers linked to the built infrastructure: The energy and transport infrastructure, the design and density of buildings, and the degree of connection of socio-economic activity.
- Institutional drivers: The architecture of urban governance, including the governance of the energy system.

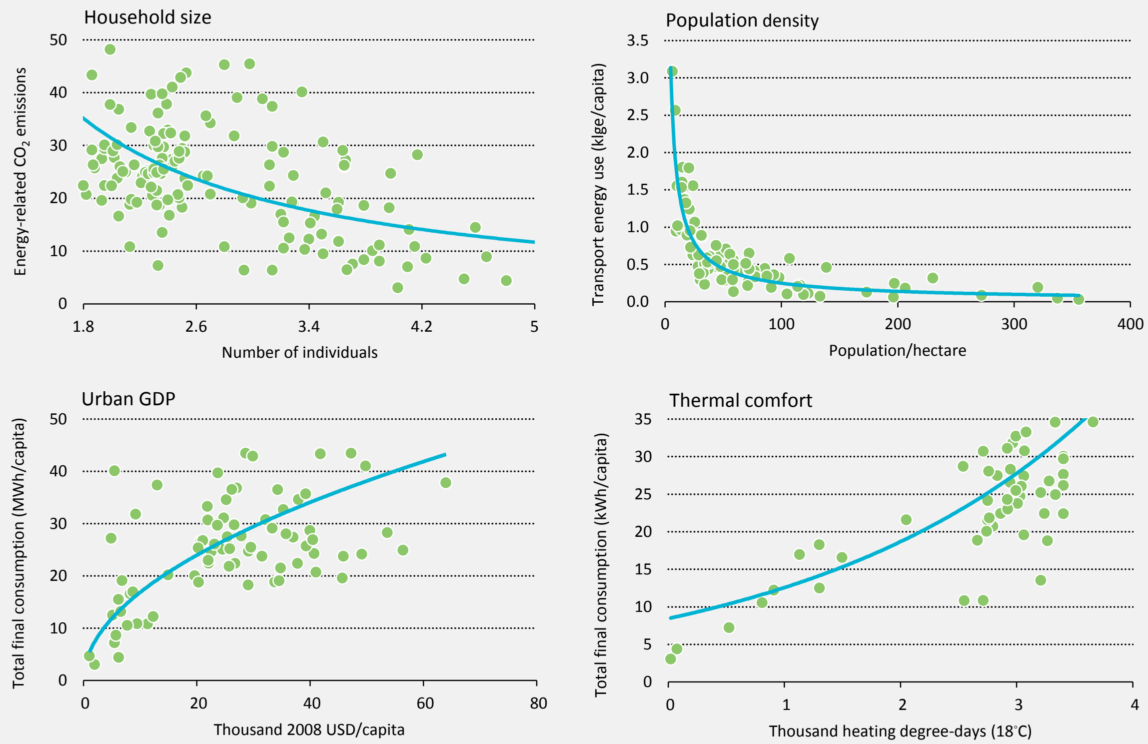
While these are distinct drivers of urban energy use, they are all linked and influence one another through strong feedbacks and synergies. City location or prevailing socio-economic structures drive the economic activity of a city, e.g. as service centres, or major transport hubs. The institutional structure and governance of a city, or the characteristics of the energy system, are in turn driven by the geophysical characteristics of a city.

Drivers linked to the geophysical environment

Climate is an important determinant of the amount of energy required to deliver urban energy services, particularly when it comes to energy demand for heating and cooling buildings, measured in heating degree days (HDD) and cooling degree days (CDD). The relationship is shown in Figure 3.9 (upper left), for a set of 67 cities. Depending on the efficiency of building envelopes, building design or secondary gains, the effect of climate can be dampened. For instance, due to a highly efficient building stock, the specific space heating demand (per capita) in Sweden, is only 15% higher than that of France, despite having nearly 2.5 times the average HDDs.

Beyond the external climate, lifestyle and cultural factors affect thermal comfort demand in cities. Above a certain income level, cooling becomes an increasingly important source of energy demand. The lion's share of future income growth will occur in emerging economies in predominantly cooling regions with energy use for space cooling. In combination with future temperature rise due to climate change, energy use for cooling is expected to be a key area of energy demand growth. The diversity of thermal sinks and sources in cities, and of energy carriers, can help integrate thermal comfort with other service demands in a cost-effective manner (e.g. through district energy networks paired with heat pumps and renewable energy sources, including excess heat from industry, or even sewage). For example, urban DHC networks (via a steam-driven chiller) can lead to primary energy needs 10-20% lower than getting power, heat and cooling separately, but capital investments are high and often more economical in dense urban areas (see Chapter 4). The urban heat island effect can also increase the use of energy for cooling buildings and contribute to smog creation through higher ambient urban temperatures, both of which intensify the sustainable energy challenge.

Figure 3.9 Selected drivers of urban energy use



Note: klge = thousand litres of gasoline equivalent.
Sources: IEA analysis based on data from UITP (2002); Kennedy et al. (2011); Grubler et al. (2012); and Creutzig et al. (2015).

Key point *Cities are complex systems, with numerous drivers of energy use and CO_2 emissions.*

Beyond climate, the geography and location of a city often determine its status as a gateway, with associated energy use and emissions from air transport and shipping.

Socio-demographic drivers

In general, final energy use tends strongly to rise as income rises (Figure 3.9 [lower left]). Household size (the number of persons per household) also affects energy use per capita. More affluent individuals tend to opt for more energy-intensive lifestyles, including higher usage of private transport, higher consumption of goods and services, and larger or detached housing units. Above three persons per household, the relationship dampens (Figure 3.9 [lower right]).

A comparison of 100 large cities shows that there is a strong correlation between density and socio-economic factors (Bertaud and Malpezzi, 2003). Despite studies finding low or no correlation between income and density, density can be strongly influenced by the inertia of social, cultural and economic factors, underpinned by the strong impacts of long-term urban policy (Lefevre, 2009).

Drivers linked to the built infrastructure

The two consumption areas directly connected to urban form and structure are transport and housing. Urban form characteristics fix distances between locations for urban activities, or encourage different travel modes. Other factors behind travel patterns include population age, gender, affluence level and employment, as well as norms, values and lifestyles. The emergent transport pattern (trip frequencies, choices of destinations, modes of traveling and trip routes) is a result of people's resources, needs and wishes, modified by the constraints and opportunities of urban form characteristics as well as other structural conditions of society.

Density of urban built infrastructure captures many of the dynamics of urban form (Figure 3.9 [upper right]). Denser cities use – all other things being equal – less energy per person in transport because average distances between residences, workplaces and service facilities are shorter. Reduced trip durations between residences, work and service locations in turn increase the opportunities for linking trip purposes, as well as shorter walking or cycling distances and a greater incentive to use public transport. Densification can also discourage private transport, for example as a consequence of narrower roads, higher congestion and a reduced number of parking spaces.

Conversely, transport is more energy-intensive where extensive road networks encourage private motorised travel, where public transport is inadequate, or where most people live in the suburbs. In urban areas with low density, private transport dominates, with a concurrent increase in the share of final energy demand for transport (higher than 65 GJ/person/yr) (Lefevre, 2009). Low-density cities with lots of space devoted to roads cannot provide the density threshold and access point convenience necessary for economically viable public transport, leading to a vicious cycle as cities develop and more space is dedicated to roads and low-density housing that comes with car ownership.

In urban areas of higher density, the distribution of modal shares is more balanced, with a higher share of public transport – typically accounting for 40% to 60% of mobility demand (Bertaud and Malpezzi, 2003). In such areas final energy demand for transport is between 15% and 25% that of low-density cities. Urban areas with an intermediate density are best exemplified by European cities, where private transport has a relatively high share but the distribution of transport is multi-modal, and where final energy demand for transport is 50% to 75% that of low-density cities (Bertaud and Malpezzi, 2003).

Beyond impacts on mobility demand, how the built environment is designed, planned and constructed can heavily influence the thermal performance of an urban area. For instance, building design factors such as orientation and thermal envelope technologies can have long-term impacts on the urban energy system, given the typical lifespan of many buildings and many building products. The type of building itself (i.e. whether it houses a single family or many households), and how densely the housing units are packed, can greatly affect the energy use of buildings. Urban zoning and opportunities for integrated, efficient energy design in buildings can also affect building energy consumption.

High density enables more compact energy distribution networks, and opportunities for DHC. DHC networks can take advantage of densities and economies of scale to meet heating and cooling needs in a more resource-efficient way than separate production units at each site of demand. Low temperature DHC in particular, i.e. reducing supply temperature to 60-70°C, can reduce distribution losses, and capture and utilise energy sources with lower thermodynamic value like industrial waste heat, biofuels or municipal waste. It can also use heat pumping technology more efficiently and improve resource utilisation through co-generation of heat and electricity. Some technologies for district energy in particular, such as waste heat use (e.g. from local industry, large service buildings or waste heat streams from underground metro), only emerge as viable options in areas of high density.

Potential for other urban energy supply options is also highly driven by density. Primary energy supply in cities is mostly limited to solar radiation, and to a much lesser extent other renewables like biomass, wind and geothermal energy. While the technical potential of solar PV on roofs and facades can meet a considerable portion of urban electricity demand (see Chapter 6), this potential is much more limited in high-density cities. In low-density cities, the solar PV potential is higher but this is counterbalanced by higher final energy demand for transport and for heating buildings.

High urban population densities can create risk for high concentration of air pollutants (even with cleaner fuels like natural gas) that can be exacerbated by local meteorological conditions. Density might also be correlated to urban heat island effects in cities (which come from absorbing radiation and waste heat from energy use for air conditioning), and can make power generation less efficient.

Matching urban energy service demands with urban energy supply

Cities are vast, dense sources of energy demand, and supply sources within cities are limited. Environmental or geothermal heat may be used for space and water heating in buildings (see Chapter 4). The rooftop areas or facades of buildings can be used to produce electricity in solar PV systems or to warm water in solar thermal modules.

Constraints on urban energy supply potential imply cities will have to rely to a great extent on energy imports to meet their total energy needs. Electricity imports can come from distant, centralised sources or more decentralised local sources on the city periphery. Centralised supply options such as large power plants may provide benefits in term of economies of scale, but may require transmission infrastructure. Fuel sources close to cities reduce transmission needs, but may result in higher specific generation costs if plant sizes are smaller. The choice between centralised or decentralised supply options may be influenced by considerations other than cost, such as resilience against supply disruptions. Peri-urban areas thus have a critical role to play (see Chapter 6).

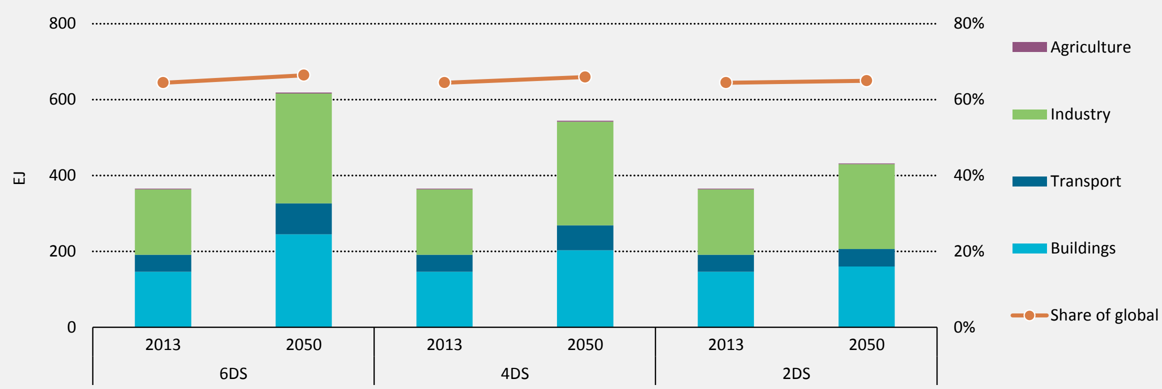
Cities represent unique energy delivery circumstances including high density of loads, variety and diversity of loads, and a breadth of distributed supply options. How urban infrastructure is designed, built and operated can yield vastly different outcomes for energy delivery. On the technology side, new developments in distributed energy resources are changing the technical and economic conditions of energy networks. Distributed PV, storage, electrification of heat and transport, and low-temperature district heating networks are creating new challenges and opportunities at the local level.

ETP urban energy system scenarios

The *ETP* 6DS, 4DS and 2DS reveal that not only will urban areas continue to dominate global energy use and emissions as the world's populations and economies continue to urbanise, but also that urban areas can play a decisive role in meeting global sustainable energy and CO_2 emissions mitigation goals. The *ETP* scenario results suggest that many energy savings and emissions reduction opportunities exist in the world's urban areas across the energy supply and end-use demand sectors. A key goal of *ETP 2016* is to explore how these opportunities can be seized, including through combinations of strong national and local policy actions, accelerated clean technology deployment, behavioural change, and greater vertical and horizontal integration of national, subnational and local energy policies.

Under the 6DS, global urban primary energy use would grow by about 70% – from 365 EJ in 2013 to 621 EJ in 2050 – as large increases in urban populations and economic activity boost demand for building energy services, mobility and industrial sector outputs (Figure 3.10). Global urban CO_2 emissions also grow rapidly in the 6DS, from 23.8 Gt in 2013 to 35.7 Gt in 2050, an increase of about 50% (Figure 3.11). As largely an extension of current trends, the 6DS demonstrates that the likely consequences of policy inaction are rapidly growing energy use and emissions by the world's urban areas, and significant risks of locking in inef cient urban plans, built environments and energy technologies that may impede transitions to sustainable urban energy systems for years to come.

Figure 3.10 **Urban primary energy use and urban share of global by scenario**



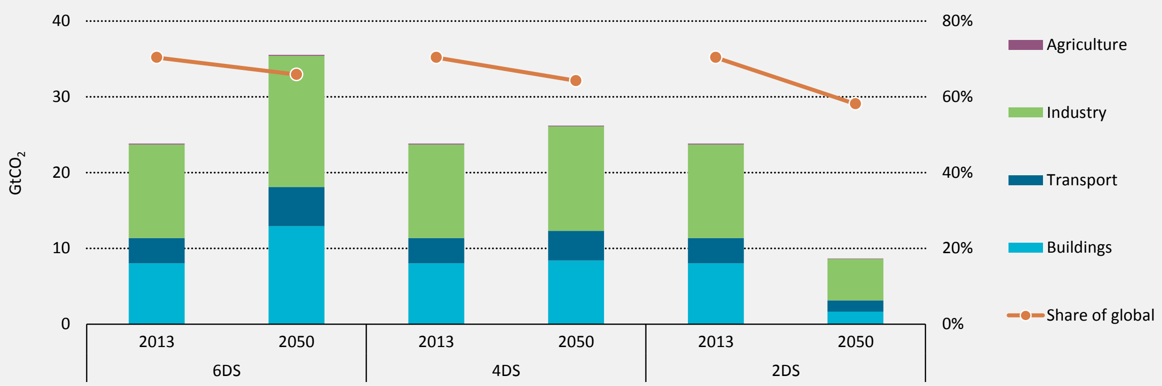
Note: Fuel inputs into the power sector are distributed to the end-use sectors proportional to their use of electricity and heat.

Key point *Under the 2DS, growth in primary energy use attributable to urban areas can be slowed considerably.*

In contrast, the sustainable energy system transformations envisaged in the 2DS can decouple urban primary energy use growth from growth in both urban GDP and urban populations. Under the 2DS, global urban primary energy use can be limited to 431 EJ by 2050, representing only an 18% increase from 2013, while urban populations are projected to increase by 67% and urban GDP by 230% over the same period. Global urban CO_2 emissions are also decoupled from energy use under the 2DS, where urban CO_2 emissions fall to 8.7 Gt in 2050, a 63% reduction from 2013 levels (23.8 Gt). The greatest improvements are associated with urban buildings, for which 2050 CO_2 emissions in the 2DS are about 75% lower than in 2013 (inclusive of direct reductions in fuel, electricity, and heat use and decarbonisation of electricity and heat supply). Urban CO_2 emissions associated with the transport and industrial sectors are also substantially reduced in the 2DS, with each sector reducing its emissions by about 55% in 2050 compared with 2013. Results for the 4DS exhibit substantial reductions in urban primary energy use and CO_2 emissions compared with the 6DS, but with many untapped energy and emissions savings opportunities compared with the 2DS.

In 2050, total urban CO_2 emissions in the 2DS amount to 58% of total global CO_2 emissions (14.9 Gt), whereas total urban primary energy use in the 2DS amounts to a higher share (65%) of total global primary energy use (663 EJ). Therefore, compared with non-urban areas in the 2DS, urban areas achieve a lower CO_2 emissions intensity per unit of primary energy use, suggesting that, at the global level, urban areas have more opportunity for rapid energy system decarbonisation than non-urban areas.

Figure 3.11 Urban CO_2 emissions and urban share of global by scenario



Note: CO_2 emissions from the power sector are distributed to the end-use sectors proportional to their use of electricity and heat.

Key point *Under the 2DS, global urban CO_2 emissions can be reduced by around 75% in 2050 compared with the 6DS.*

The substantial reductions in urban primary energy use and CO_2 emissions associated with 2DS pathways underscore the importance of strong, near-term policy actions to enable and accelerate sustainable urban energy system transitions. Many of these near-term actions can be taken by national governments, and may be imperative for meeting national energy sustainability goals in an increasingly urbanised world. Such near-term actions include increased investments in energy technology RD&D; development of energy ef ciency standards for buildings, industrial processes and energy-using equipment that inf uence urban energy use; supporting public-private partnerships to spur innovations and urban technology diffusion; developing stronger national, subnational and local energy policy synergies; and facilitating sharing and leveraging of best practices among urban areas. These and other actions and opportunities are discussed elsewhere in *ETP 2016* in greater detail:

- Building energy use and CO_2 emissions can be substantially reduced through deep retrofits of existing buildings to improve thermal performance (i.e. space heating and cooling ef ciencies); aggressive energy performance standards for new buildings; accelerated adoption of ef cient lighting, appliances and other energy-consuming equipment; and greater use of DHC systems as part of an integrated, low-carbon, sustainable buildings sector (Chapter 4).
- "Avoid, shift and improve" strategies can yield significant energy and emissions savings in urban transport systems. Transport activity can be avoided through pricing policies and urban planning related to density and urban form. Improving the viability of public transport and non-motorised modes can help shift transport activity toward less energy- and carbon-intensive modes. Vehicle ef ciency can be improved through a range of policies, including removal of fuel subsidies; fuel taxation; aggressive fuel economy and emissions regulations; and greater diffusion of EVs (Chapter 5).

- Urban energy systems can be made more sustainable through greater use of local energy sources and through investments in infrastructure that deliver cleaner and more secure electricity, heat and fuels, and that maximises integration opportunities using smart grids. Under the 2DS, electricity becomes the dominant final energy carrier, while realising the technical potential for rooftop PV could provide a sizeable share of the electricity required by cities in 2050. Greater use of energy recovery from municipal solid waste, landfill gas, sewage and industrial excess heat can provide additional low-carbon energy opportunities for cities. Standardisation and interoperability of smart grids will be necessary to integrate energy systems (Chapter 6).
- The global industrial sector can significantly reduce its energy use and CO_2 emissions by improving process energy efficiencies, switching to low-carbon fuels where feasible, improving materials efficiencies, and adopting innovative processes including CCS technologies. These transitions will require a combination of accelerated technology deployment and assertive policy instruments (Chapter 1).

Furthermore, *ETP 2016* analysis finds that achieving the 2DS for urban buildings and transport systems in particular would not place significant burdens on the global economy. For urban buildings, the additional cumulative investments required to achieve the 2DS (compared to the 6DS) are estimated at USD 11 trillion between 2013 and 2050 (equivalent to less than 0.15% of the cumulative GDP over the same period), which include investments in efficient appliances, space heating, water heating, and space cooling equipment, lighting, and building envelope measures. For urban transport systems, avoid and shift options in the 2DS lead to negative additional cumulative investments of USD -21 trillion between 2013 and 2050 compared to the 6DS, driven by significant reductions in required passenger vehicle purchases and associated passenger vehicle transport infrastructure investments.

The role of urban energy system policies

Tapping the significant energy and emissions savings potential that cities offer requires overcoming several cost, regulatory, capacity, infrastructural and behavioural barriers to sustainable energy deployment. Energy systems are characterised by a complex web of interactions among national, subnational and local policy makers as well as businesses, households and non-governmental organisations. Local planners, however, can lower these barriers by leveraging a broad array of policy measures and tools. National policy makers have a crucial role in ensuring support and ensuring that the required level of vertical integration between the national and local level is in place to enable local policy makers to successfully drive urban sustainable energy transitions (see Chapter 7).

Urban energy policy design depends on a range of local factors. For example, rapidly growing cities in developing countries need to lift large populations out of poverty, so improved energy access plays a critical role. This pressure may favour energy technology solutions that can be deployed quickly and cost-effectively, rather than long-term policies such as master urban plans. Such pressures must also be counterbalanced with the recognition that technologies and urban plans deployed today can lead to path dependency and technology "lock-in", which affects the viability of future energy pathways.

In the hands of national policy makers, some tools, such as carbon taxes or minimum performance standards, affect the way energy is consumed and produced in cities and non-urban areas. Other national policy levers can selectively target urban energy patterns. For instance, national legislative frameworks can provide greater powers to cities in areas where they have greater competitive advantage, e.g. in land use and local transport. National policies for local land use and transport planning can provide cities with the legislative powers, human resources and financial instruments necessary to implement integrated planning. In a similar way, national or state legislation is often needed to enable innovative utility business models to be tested or novel financial mechanisms to be rolled out. Support from national governments can also include capacity-building programmes for local planners, mandatory ef ciency benchmarks for self-governing and funding programmes for sustainable infrastructure investments.

These opportunities can be seized through greater alignment and synergies between national and local policies. This vertical integration (Broekoff, Erickson and Lee, 2015) is particularly important for small and medium-sized urban areas, which will absorb much of the world's future urban population growth, but typically have limited governmental capacity and resources for comprehensive policy action.

Local policy makers have a wide range of options to support the uptake of sustainable energy technologies. In this "horizontal approach", policies can be classified according to the degree of legislative assertiveness (carrot versus stick approach), the targeted groups (e.g. residential energy users, enterprises), the dimensions of energy sustainability addressed (e.g. climate change mitigation, air pollution, access to modern energy services), or the functional areas of the city authority, where local city planners – in a similar way as national policy makers – can play different roles as regulators, planners, enablers, or "green" stewards of municipal assets (Table 3.2).

Table 3.2 Urban policy mechanisms to support sustainable energy diffusion

Self-governing	Service provision	Enabling	Regulation and planning
Schemes for improving the energy efficiency of existing municipal buildings (e.g. internal revolving funds).	Setting minimum quotas for renewable energy or co-generation provided by municipally owned utilities.	Sustainable energy education projects in schools.	Integrated land use and transport planning. Strategic plans in the areas of energy, climate change, environment and water.
Mandated construction of near-zero or zero-energy municipal buildings.	Direct infrastructure investments (e.g. district heating networks, cycle lanes).	Awareness and promotional campaigns.	Mandatory installation of solar water heating/solar PV systems in new buildings.
"Greening" of municipal vehicle fleet.		Facilitate co-operation among stakeholders (e.g. public-private partnerships).	Emissions and mileage standards for public transport vehicles (buses, taxis).
Green procurement rules for energy-efficient appliances.		Capacity building (e.g. training of local technicians on certification of building energy performance).	Minimum energy intensity standards for new buildings or buildings undertaking deep renovation.
Low-carbon, distributed energy supply in public buildings.			Road-user charging, congestion charging, parking fees.
			Property and land-value taxes.

Sources: Kern and Alber (2008); OECD (2010).

Policy measures can be bundled together in comprehensive urban plans that aim to enhance several components of the energy system to achieve broad policy goals, such as improving energy sustainability, economic development, environmental protection and social equity. Many cities have developed sustainable energy plans or climate action plans that aim to improve energy ef ciency, reduce the carbon intensities of energy supplies and limit GHG emissions, often with concrete targets (e.g. for CO_2 emissions reductions by a given year). For example, a number of global cities have committed to reporting emissions inventories, climate change mitigation and adaptation plans, and annual progress towards emissions targets through several reporting platforms such as the carbon*n*® Climate Registry (Deng-Beck and van Staden, 2015) and the CDP Cities Program (CDP, 2016). Structured guidance exists for cities to conduct emissions inventories in a transparent and consistent fashion (GHG Protocol, 2015). Several cities have issued broad sustainability plans that not only include energy and climate goals but also aim to enhance liveability, innovation, social inclusion and economic development (Box 3.5). A clear action plan with concrete targets is a critical way for urban policy makers to make public commitments, improve transparency, and measure and communicate progress towards sustainability goals. For example, in the European Union, the Covenant of Mayors initiative (Box 7.1) has been supporting the design and implementation of Sustainable Urban Energy Action Plans in hundreds of European cities.

Box 3.5 Smart City Wien Framework Strategy

In June 2014, the Vienna City Council adopted the Smart City Wien Framework Strategy to establish a long-term structural framework for governance, plans and programmes to achieve its sustainability goals to 2050 (Vienna City Administration, 2014). The framework exemplifies several key ways cities can realise their potential to make their energy systems sustainable.

Holistic approach

The Smart City Wien Framework Strategy recognises that for cities to prosper, long-term energy system strategies need to meet several social and economic objectives. The framework encompasses three central objectives to achieve the city's holistic vision:

- radical resource preservation, which requires intelligent use of resources and energy efficiency in mobility, buildings, urban infrastructure (waste, water and information and communication technologies [ICT]), power and the grid
- high and socially balanced quality of life, which favours energy solutions that ensure social inclusion, including affordable housing, economic development opportunities, and access to infrastructure and energy services
- innovation to accelerate transitions and enable prosperity for all with particular focuses on the economy, ICT, education, research and science.

Clear goals and targets

To meet Vienna's three central objectives, city planners included specific goals and timelines for priority areas at a level that facilitates monitoring and review. Goals and timelines related to climate change were further aligned with overarching EU targets to ensure vertical policy synergies. These strategies help provide transparency, policy stability and clear market signals to enable the needed transitions. Some key examples of specific goals include ensuring that:

- energy efficiency increases and final energy consumption per capita decreases by 40% by 2050 (from 2005 levels)
- over 20% of Vienna's gross energy consumption comes from renewable sources by 2030 and 50% by 2050
- commercial traffic originating and terminating in Vienna is largely CO_2-free by 2030
- all new structures, additions, and refurbishments from 2020 meet cost-optimised, zero-energy building standards.

Co-operation to find smart solutions for complex problems

The Smart City Wien Framework Strategy was designed with inputs from, and incorporates co-ordinated actions among, all major departments of city governance. This approach enables close collaboration across departmental, thematic and even municipal boundaries to accomplish increasingly complex tasks with tight resources. The strategy comprises many core areas of urban life, including housing, jobs, safety, education and green spaces. It also strives to involve private and municipal enterprises, as well as partners from the economy, research, science and other fields to achieve joint goals.

A focus on innovation

The Smart City Wien Framework Strategy targets growth in innovation to enable its energy transitions, a strong economy, and leadership in research, education and quality of life. The city aims to become one of the five biggest European research and innovation hubs by 2050, and to encourage 10 000 people annually to set up enterprises in Vienna. The city has placed a particular emphasis on ICT for enabling economic growth while improving sectors such as energy, transport, housing, health, and environment for both inhabitants and businesses. Vienna is investing in ICT pilot projects, infrastructure, and a wireless local area network across the city.

Cities can use a range of finance mechanisms to pay for sustainable energy investments while modifying energy use. General tax measures such as property or land value taxes can be structured to encourage compact and dense development (see Chapter 7). Congestion charges, parking fees and high-occupancy toll lanes can significantly reduce the use of personal vehicles while providing an important source of revenue to cities. User fees on electricity and heat bills from municipal utilities can help overcome non-market barriers to energy ef ciency.

Furthermore, building permits and development fees can not only encourage compact development but also stimulate a market for high-ef ciency buildings. This goal could be achieved by linking building permit fees to the certified energy performance of the building, where the developer would pay the highest up-front fee based on the minimum energy performance standard and then receive compensation after construction if the certified energy performance is above the minimum. Innovative taxation approaches are also increasingly being adopted by cities, such as land value capture and tax increment financing.

Cities can also obtain funds for sustainable energy investments by borrowing from the financial sector. Local authorities can negotiate interest rates on loans lower than would apply to private enterprises, because the loan can be backed by the fiscal leverage of cities. Municipal green bonds can also be issued to support new energy infrastructure.

Cities can greatly enhance the effectiveness of sustainable energy policies by participating in international city networks (Box 3.6).

Technological change is the central driving force behind the 2DS, as well as the goal of many sustainable urban energy system policy recommendations in *ETP 2016*. Understanding the role of technological change requires policy makers to consider current sources of urban energy demand and supply across relevant sectors, the effects of key drivers of energy demand and supply choices (e.g. due to population and economic growth), and the expected costs and benefits (e.g. energy savings and emissions reduction) of different technology deployment scenarios. While some cities, countries and organisations are making considerable progress on urban-scale energy statistics (CDP, 2016; UK DECC, 2015; WCCD 2016), many cities still lack the necessary energy use data, technology data and analytical capacity for rigorous quantitative evaluation of policy options.

Box 3.6 International city organisations

Several international organisations have been created over the past years to support cities in a variety of ways, including capacity building (e.g. through knowledge sharing and training), benchmarking and facilitating access to funding. Three of these organisations are the C40 Cities Climate Leadership Group (C40), ICLEI—Local Governments for Sustainability (ICLEI), and United Cities and Local Governments (UCLG), which have partnered together to create the Compact of Mayors.

C40 connects more than 80 of the world's largest cities, representing more than 550 million people and one-quarter of the global economy. C40's mission is to tackle climate change and drive urban action that reduces GHG emissions and climate risks, while increasing the health, well-being and economic opportunities of urban citizens. Working across multiple sectors and initiative areas, C40 convenes networks of cities, providing a suite of services in support of their efforts, including direct technical assistance; facilitation of peer-to-peer exchange; and research, knowledge management and communications. C40 is also positioning cities as a leading force for climate action around the world, defining and amplifying their call to national governments for greater support and autonomy in creating a sustainable future (C40, 2016).

ICLEI is an international association of local governments committed to building a sustainable future, with over 1 000 member cities, towns and metropolises in 86 countries. ICLEI supports its members (which account for 20% of the global urban population) in making their cities sustainable. Established in 1990, ICLEI has 25 years' experience in supporting local climate action worldwide. ICLEI offers local and subnational governments from around the world support and access to: networking and peer exchange opportunities; a knowledge and contact bank of good practices, experts and solution providers; institutional capacity building and technical consulting on innovative technical, organisational, financial and social solutions; information and standards on sustainability; methodologies and tools; and global advocacy services that aim for the appropriate recognition, engagement and empowerment of local governments as governmental stakeholders in the global efforts. ICLEI facilitates several thematic communities of practice, including on building efficiency, district energy and the 100% Renewable Energy Cities and Regions Network (ICLEI, 2016).

UCLG's work programme is aimed at "increasing the role and influence of local government and its representative organisations in global governance; becoming the main source of support for democratic, effective, innovative local government close to the citizen; ensuring an effective and democratic global organisation" (UCLG, 2016).

The Compact of Mayors is a coalition of cities launched at the 2014 United Nations (UN) Climate Summit by UN Secretary-General Ban Ki-moon and his special envoy for cities and climate change, Michael R. Bloomberg. This initiative was created under the leadership of C40, ICLEI and UCLG with the support of UN-Habitat. The Compact establishes a common framework to assess the impact of cities' actions through standardised measurement of emissions and climate risk, and also through public reporting of efforts (Compact of Mayors, 2016).

To make more effective decisions, local and national policy makers need to invest in compiling robust urban energy statistics, including the required capacities and systems for data collection, verification, storage and analysis. Further investments are needed in building and maintaining the analytical capacities necessary for quantitative policy evaluation, which can help policy makers pursue the most cost-effective and appropriate clean technology pathways. Some cities are benefiting from the use of urban energy system simulations and models to evaluate planning decisions (Box 3.7).

Box 3.7 Modelling of urban energy systems

Making the transition to sustainable urban energy systems requires innovative policies to accelerate deployment of clean energy technologies while balancing economic, social and environmental goals across different planning horizons. The appropriate mix of policies, technologies and implementation schedules varies widely based on local factors such as resource availability, government capacity, climate, affluence, and trends in population and economic structure. This complex web of considerations can make decision making difficult for many urban planners, especially those without strong analytical capacities or data on local energy system characteristics and trends.

Urban energy system models can reduce these barriers by providing decision makers with a virtual platform for assessing different policy and technology strategies. Such models exist for specific urban energy system components, such as transport networks, and for more integrated considerations of the built environment and energy supply networks at the city scale (Keirstead, Jennings and Sivakumar, 2012). Given their complexity, many models are focused on academic studies and research. However, increasingly such tools are being made available to decision makers for conducting "what if" analyses and for exploring the energy use, emissions, and cost implications of different urban planning decisions.

For example, the Technologies and Urban Resource Networks (TURN) model, developed by Imperial College London was used to explore different options for building efficiency and energy supply improvements in Newcastle-upon-Tyne. A range of options were considered on the demand side (including improvements to insulation, windows and occupant behaviours) and the supply side (including renewables, CHP and efficient boilers). The results highlighted priorities for the city, including curtailing the growth of electricity demand, installing efficiency measures as soon as possible, and using domestic renewable energy technologies, CHP and decarbonised grid electricity (Keirstead and Calderon, 2012).

Another example comes from the Future Cities Laboratory, part of the Singapore-ETH Centre for Global Environmental Sustainability, a joint venture between ETH Zürich (the Swiss Federal Institute of Technology) and Singapore's National Research Foundation. The Future Cities Laboratory uses the stocks and flows approach to model the urban metabolism in a modular way: typical stocks and flows are people, water, material, energy, transportation, finances, space and information. Urban designers can create design scenarios that then can be analysed with regard to stocks and flows, and translate the results of simulations into urban design. These activities, visualised and recorded in a large simulation platform (Schmitt, 2013), led to the discovery of new relationships between energy and other urban stocks and flows, and their impact on quality of life in cities.

These examples underscore the important role for models in urban energy planning decisions. However, additional investments are needed to continuously improve modelling methods, data availability, decision relevance, and analytical capacity in governments so that such models can be incorporated into the decision making process on a wider and more frequent basis.

Recommended actions for the near term

To take advantage of the significant potential of urban areas to contribute to the global transition to cleaner energy systems, national and local governments should establish governance structures that strengthen the enabling environment for clean energy technologies at the urban scale. National government actions will be particularly important for small and medium-sized urban areas where government capacities and resources are typically limited. New government structures should emphasise greater alignment among national, regional and local policies (vertical integration) and greater collaboration and co-operation between local agencies (horizontal integration), to meet environmental, economic and social objectives simultaneously at both local and national levels.

Increased participation from local inhabitants and economic players should be fostered to identify policy and technology solutions that meet the needs of all stakeholders. Such participation can be facilitated by establishing holistic, inclusive, sustainable urban action plans. Such plans should address a range of sustainability goals; define transparent objectives, metrics and targets over the short and long term; and commit to regular monitoring and evaluation of progress.

National and local governments should also seize the opportunity for cities to act as innovation hubs and test beds for sustainable urban energy technologies and systems. The density of human, economic and intellectual capital in cities can help accelerate clean technology development and deployment by enabling connections between local private and public entities with capabilities across the technology cycle. Governments should further support and accelerate public-private partnerships for clean technology development, demonstration and deployment, and commit to sharing and promoting best practices to accelerate and broaden adoption of clean energy solutions.

The *ETP 2016* 2DS demonstrates that significant energy savings and emissions reduction opportunities exist in the world's urban areas across the energy supply and end-use demand sectors. To achieve this transition, national and local governments must increase and accelerate investments in clean technology RD&D, particularly for core technology areas most relevant to urban energy systems: advanced building and mobility technologies, DHC systems, smart grids, energy storage, and more energy- and materials-efficient industrial production technologies.

At the local level, zoning policies should encourage greater population and employment densities. Making cities denser can increase the economic viability of public transport systems, reduce transport system energy demand by enabling greater use of non-motorised transport modes (walking and biking), and provide energy-efficient, multi-family residential living spaces. Denser cities should allow and encourage mixtures of residential, commercial and industrial properties, while providing accessible and adequate green spaces for urban inhabitants. National governments can assist local zoning authorities by facilitating the sharing of best practices, expertise and urban planning guidance among major urban areas.

To accelerate the transition to sustainable urban energy systems, policy makers require robust urban energy statistics so they can identify and prioritise major contributors to energy use and emissions, establish energy and emissions baselines, and monitor and communicate progress towards national and local energy and emissions goals. National and local governments must invest in data collection, processing and analysis capabilities to generate urban-scale data on an ongoing basis. This will also enable benchmarking and comparison of urban energy use and emissions at national, regional and global levels.

Substantial investments are also needed to develop and maintain urban energy system models and planning tools that can improve the robustness of urban planning decisions and enable complex, multi-criterion planning decisions. It is equally important to invest in building and maintaining institutional analytical capacities for using such data and tools, to enable more robust and effective urban energy technology and policy decisions.

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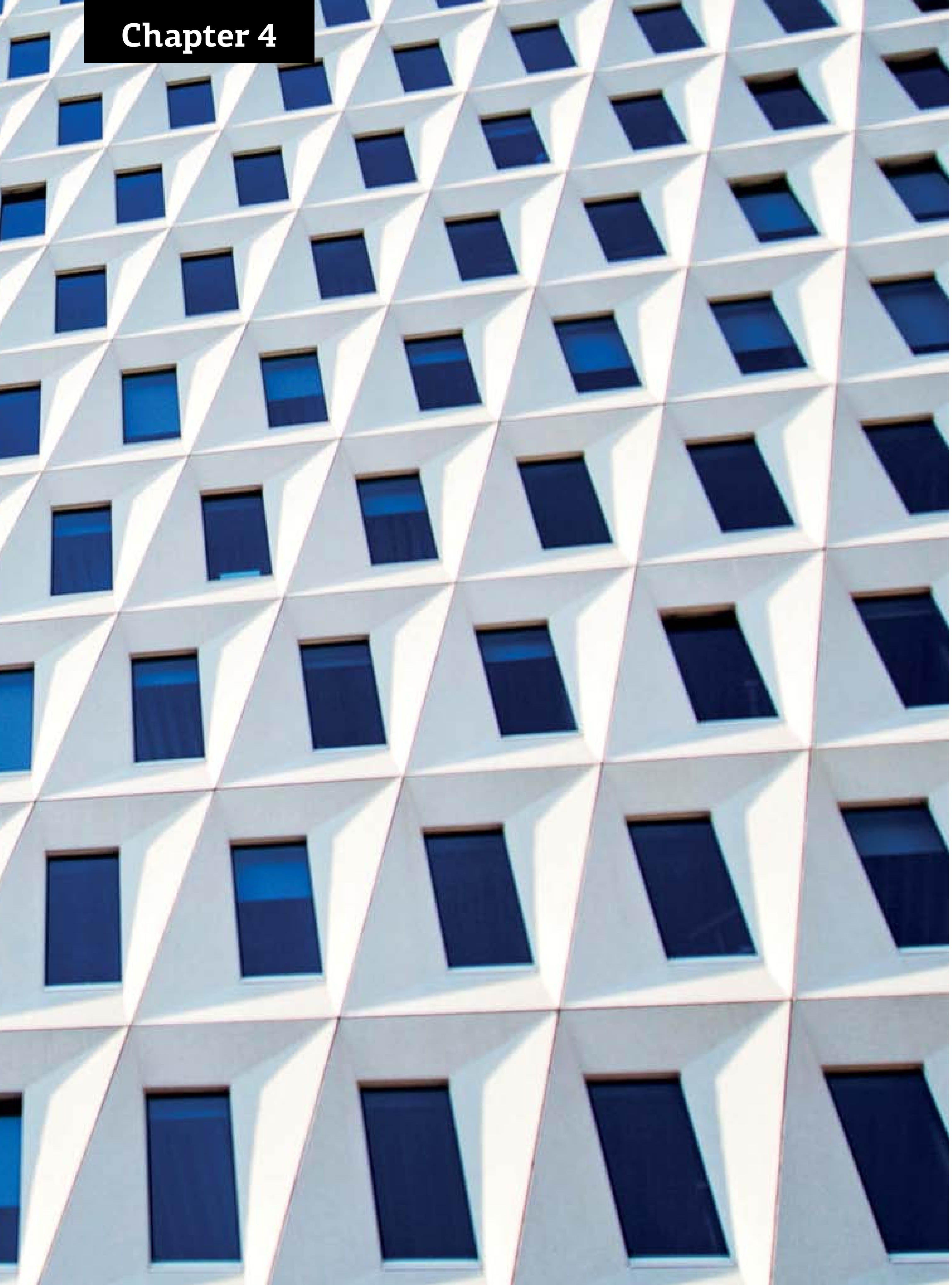
Chapter 4



Energy-Efficient Buildings in the Urban Environment

Rapid expansion of the global built environment and ownership of energy-consuming technologies will have a major impact on building energy use to 2050. Urban areas offer an important opportunity to improve building energy efficiency and realise low-carbon, integrated energy communities. A specific focus is needed on technologies and policies for low-energy new buildings and deep energy renovation of existing buildings.

Key findings

- ***The global buildings sector consumed nearly 125 exajoules (EJ) in 2013, or over 30% of global final energy consumption, accounting for nearly one-third of global carbon dioxide (CO_2) emissions when upstream power generation is included.*** *Total energy consumption in urban buildings was an estimated 78 EJ, or more than 60% of total building final energy use.*

- ***Urban building energy consumption under the 6°C Scenario (6DS) grows by as much as 70% over 2013 levels, meaning that more than 90% of expected energy growth in global buildings is likely to occur in urban areas.*** *In developing countries, urban building energy consumption more than doubles by 2050.*

- ***Urban CO_2 emissions increase from 7.5 gigatonnes of CO_2 ($GtCO_2$) in 2013 to nearly 12 $GtCO_2$ in 2050 under the 6DS.*** *Roughly 85% of urban building CO_2 emissions come from upstream power generation in 2050 (compared with 75% today), due to continued growth in urban electricity demand.*

- ***Space heating and cooling continue to be critical areas of needed action.*** *Space heating accounts for more than one-third of global building energy use and continues to be the largest end use in both the 6DS and the 2°C Scenario (2DS) to 2050. Space cooling, while a smaller portion of energy demand in buildings today (roughly 5%), is the fastest-growing end use and could increase by as much as tenfold in some regions if concerted effort is not made to improve building envelope and equipment efficiencies.*

- ***If aggressive energy efficiency policies are pursued in line with the 2DS, urban building energy consumption is reduced by 30% in 2050 compared with the 6DS.*** *Urban areas account for more than 75% of global building energy reductions under the 2DS.*

- ***Energy efficiency measures and fuel switching away from fossil fuels under the 2DS lead to a 50% reduction of direct CO_2 emissions in urban buildings in 2050 compared with the 6DS.*** *Indirect emissions (from upstream generation of electricity and commercial heat) decrease by 93%. The majority of CO_2 emissions savings in urban buildings are achieved in space heating and cooling.*

- ***Low-energy new buildings, deep energy renovations of existing buildings, and low-carbon, energy-efficient heating***

and cooling technologies are the most important means to reduce emissions from buildings in urban areas. *Energy efficiency measures in buildings can also achieve multiple benefits for local communities, including job creation, improved air quality, more affordable energy, reduced maintenance costs and more stable energy networks.*

- ***While zero-energy buildings (ZEBs) and near-zero energy buildings (nZEBs) are technically feasible in urban areas, challenges (e.g. high urban densities and limited on-site renewable potential) may limit their achievement.*** *Efficient district heating and cooling (DHC) in combination with heat pumps and renewables, can play a vital role in achieving low-carbon and even carbon-neutral communities.*
- **Integrated building and district energy measures can help cost-effectively meet energy and emissions targets to 2050.** *A strategic long-term vision will be necessary to encourage the effective planning and implementation of building renovation measures with district heat network investments.*

Opportunities for policy action

- *Local planning and policy design can play an important part in meeting targets related to building energy efficiency. This influence includes local enforcement of mandatory building energy codes. Further energy savings can be achieved with voluntary initiatives, labels or incentives to engage local consumers and building stakeholders.*
- *One critical policy is the promotion and regulation of more efficient building energy-consuming equipment (e.g. appliances, lighting and heating equipment) through labelling and minimum energy performance standards (MEPS). Currently, only 30% of energy consumption in the buildings sector is covered by energy efficiency regulations. This level of coverage needs to be expanded to apply to the majority of building energy-consuming equipment and end uses.*
- *National policies have substantial leverage to enable effective, sustainable urban energy planning through the setting of mandatory MEPS and building energy codes. These policies can also provide transparent, consistent approaches to urban areas that may not have the resources or capacity to design their own standards or labelling programmes.*
- *In emerging markets, new construction in cities offers a unique opportunity to address increasing energy demand through energy efficiency measures, building design and urban planning. National support to provide training and capacity tools is an important first step to enabling local action.*
- *In mature economies, urban densification and deep energy renovation of existing buildings can reduce the energy footprint of the buildings sector. Financial and regulatory tools can enable market conditioning and widespread adoption of deep energy efficiency measures.*
- *National and local governments can support advanced building components and energy-efficient technologies through appropriate pilot programmes and financial incentives to help establish local market demand.*
- *With national support, city governments can lead through deep energy renovation of public buildings. Local energy efficiency programmes and incentives (e.g. low-interest loans, tax rebates, and zoning or planning exemptions) can also support deep energy renovations in the private sector to ensure that the process becomes widely available and is standard practice.*
- *The integration of modern district energy networks and energy-efficient buildings, in combination with heat pumping technologies and renewable energy sources, can be a valuable opportunity to achieve cost-effective, low-carbon communities in urban areas. Greater co-ordination and financial support are needed to create a long-term stable market for building and district energy stakeholders.*

This chapter outlines the rationale and strategic opportunities for energy efficiency action in urban buildings with respect to 2DS objectives for a sustainable, low-carbon buildings sector. It recommends actions that need to be taken up to 2050 to achieve those objectives relative to the three *Energy Technology Perspectives 2016 (ETP 2016)* energy scenarios:

- the 6DS, in which building developments beyond current policies are limited and technology improvements continue to be incremental
- the 4˚C Scenario (4DS), which takes into account building energy policies that would improve the energy efficiency of most end-use technologies but that would not sufficiently address deployment of advanced building technologies or deep energy renovations across existing buildings
- the 2DS, which is consistent with the goal of limiting the global average increase in temperature to 2°C and includes deployment of highly efficient building energy technologies along with rigorous building energy codes and deep energy renovations of the existing building stock before 2050.

The following sections examine the chief energy technology and policy priorities for urban buildings as well as policy actions needed to realise the anticipated energy and emissions reductions to 2050 under the 2DS. The chapter focuses on space heating and cooling demand in urban buildings, as that demand accounts for a major portion of building energy use. Three detailed case studies in Sweden, Italy and China explore cost-effective, integrated technology options for meeting low-carbon, energy-efficient heat demand. Finally, the chapter considers market conditions and policy recommendations needed to put cities and the global buildings sector on a 2DS pathway.

The global buildings sector consumed nearly 125 EJ in 2013, or over 30% of total final energy consumption[1] for all sectors of the economy, with global building energy consumption having increased by 35% since 1990. Nearly three-quarters of building energy use was consumed in the residential subsector alone.[2] Buildings also accounted for half of global electricity demand, with electricity consumption increasing by more than 500% in some regions since 1990. When upstream power generation is taken into account, the buildings sector represents slightly less than one-third of global CO_2 emissions.

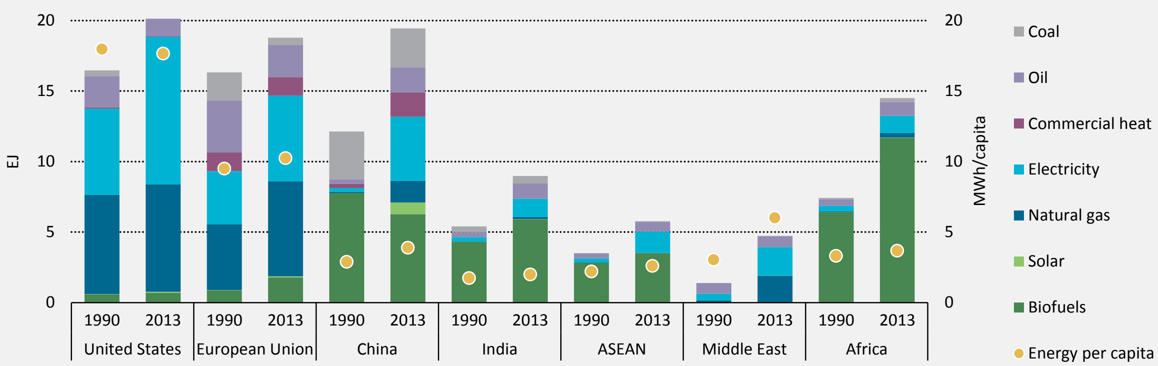
Space heating and cooling demand continues to be a critical area of needed action in the buildings sector. Space heating currently accounts for more than one-third of global energy use in buildings and will continue to be the single largest energy-consuming end use to 2050 in both the 6DS and the 2DS. Space cooling, while a significantly smaller portion (roughly 5%) of energy demand in buildings today, is the fastest-growing end use in buildings and could increase by as much as tenfold to 2050 in some warm-climate, rapidly emerging economies (e.g. Mexico and India). This growth will also have an important effect on the grid, because peak electricity demand for space cooling can stress ageing or at-capacity power sector infrastructure. Concerted effort is therefore needed to improve building envelope efficiencies and to reduce growing global demand for mechanically conditioned thermal comfort.

Globally, building energy performance (as measured by final energy per floor area) has improved since 1990 – from an annual average of more than 230 kilowatt hours per square metre (kWh/m^2) in 1990 to roughly 160 kWh/m^2 in 2013. Development and enforcement of building energy codes and energy efficiency policies have helped to offset growth in total

1 Energy consumption here refers to final energy use, unless otherwise noted.
2 See Chapter 1 on the global outlook for additional details on global buildings sector energy consumption.

energy consumption. However, the simultaneous effect of growing global wealth, which typically corresponds to demand for larger spaces (i.e. more square metres per person), smaller household[3] size (i.e. fewer persons per household), and increased demand for energy services and comfort, have offset many of those efficiency gains. As a result, overall building energy consumption on a per capita level has remained practically constant at 5 megawatt hours (MWh) per person per year since 1990. Some countries, such as the United States, Sweden and France, have been able to reduce energy consumption per person through aggressive building energy policies, but most countries have not decoupled building energy use from population growth (IEA-IPEEC, 2015). In many developing regions, and even in some developed countries, energy use per person has increased since 1990 (Figure 4.1).

Figure 4.1 **Building final energy consumption and intensity per person in select regions**



Notes: Figures and data that appear in this report can be downloaded from www.iea.org/etp2016; ASEAN = Association of Southeast Asian Nations; Commercial heat refers to heat produced for sale (e.g. district heat) and that is available for consumption by final end users; Biofuels mainly comprise traditional sources such as fuelwood, charcoal, agricultural waste and dung; Figures and data that appear in this report can be downloaded from www.iea.org/etp2016.
Source: IEA (2015a), *IEA World Energy Statistics and Balances* (database), www.iea.org/statistics.

Key point *Few countries have decoupled building energy use from population growth. Energy efficiency is crucial to offsetting building energy growth while still providing comfort and improved quality of life.*

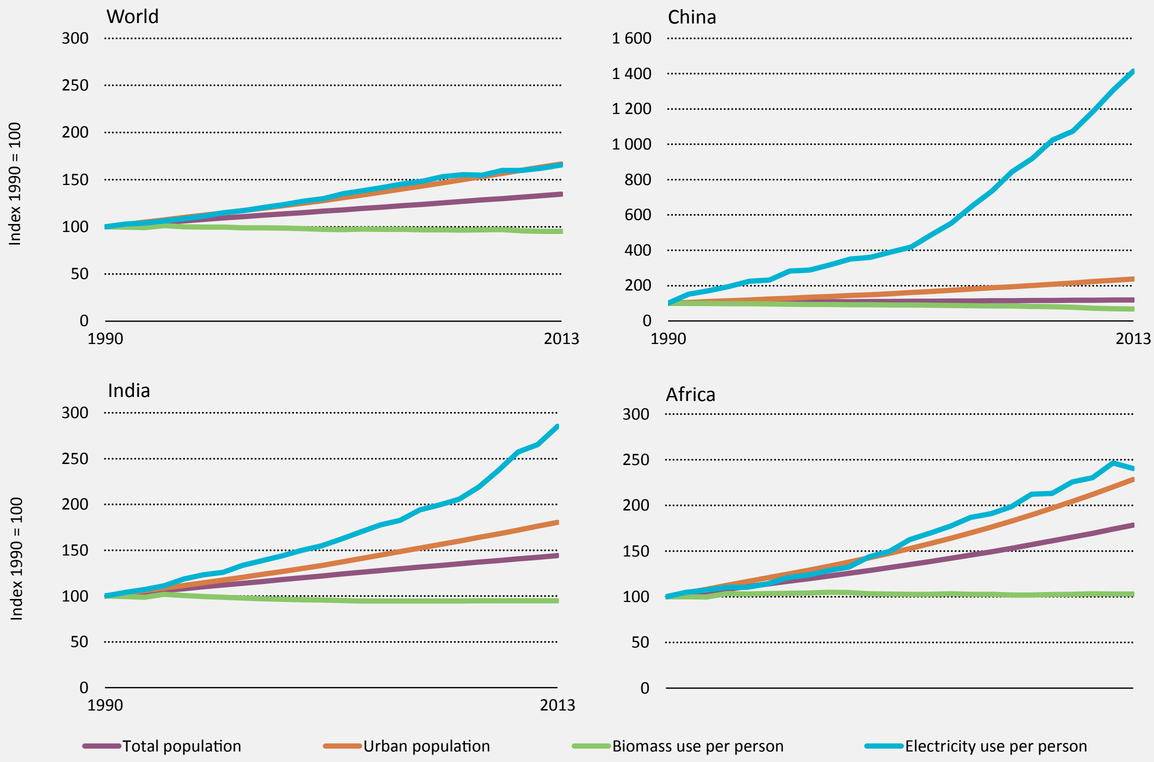
Urbanisation has also played a strong role in building energy trends since 1990. In developing countries, urbanisation is typically associated with increased access to and use of energy services, resulting in less use of biofuels (e.g. traditional solid biomass and dung) for heating and cooking and increased use of electricity. Globally, traditional use of biomass and other biofuels consumption in the buildings sector decreased by 6% in 1990 to 1.3 MWh per person in 2013. Average electricity consumption per person increased by more than 65% to 1.5 MWh per person during the same period (Figure 4.2).

In rapidly emerging economies, such as China, India and Indonesia, electricity use per capita increased as much as threefold (India) to fourteen-fold (China) since 1990. Annual biomass consumption per person decreased slightly in each country during the same period. These trends can be explained partly by strong policy focus on electrification and energy access over the past two decades and less focus on improving the efficiency of biomass

3 The terms “household” and “dwelling” are sometimes used interchangeably. For statistical purposes, “household” is used in this chapter. Any reference to “dwelling” simply refers to a place of residence (which may or may not be the principal place of residence for a household).

use (e.g. through clean cook stoves). Given that the population of developing countries is expected to increase by another 40% by 2050 (UN DESA, 2013), significant effort is needed to expand current urbanisation and building energy policies to enable energy efficiency that improves comfort and quality of life.

Figure 4.2 **Changes in key energy drivers of building energy consumption for select regions**



Note: The graph does not provide information on the relative contributions of various drivers to building energy use, but rather shows various trends for building energy use relative to population growth.
Source: Population: UN DESA (2013), *World Population Prospects: The 2013 Revision, Medium-Fertility Variant;* UN DESA (2014), *World Urbanisation Prospects: The 2014 Revision,* calculations derived with IEA (2015a), *IEA World Energy Statistics and Balances* (database), http://dx.doi.org/10.1787/data-00512-en.

Key point *Globally, electricity growth in the buildings sector has been linked to urbanisation. Aggressive energy efficiency measures will be critical to decoupling this trend.*

Several energy policy measures can act together to decouple global population growth, increasing wealth and expected urbanisation trends from aggregated building energy consumption. These measures include:

- rigorous and enforceable building energy codes for new construction
- building energy codes and/or mandatory energy performance standards for existing buildings when they undergo renovations
- appliance standards and labelling

- whole-building rating, labelling and disclosure programmes
- educational programmes and capacity building[4].

Additionally, energy policy measures that reflect the true costs of energy to end users (e.g. phasing out of fossil fuel subsidies) can encourage energy efficiency and energy conservation. However, these policies can be controversial.

Many buildings sector energy policies and technology priorities are set on the national scale, but cities can play an important part in meeting 2DS objectives to 2050 (Box 4.1). As a policy bridge from national to local building stakeholders, municipal authorities serve a vital function in implementing, monitoring and enforcing building energy policies. This function can include local building energy codes for new construction and existing building renovation, which contribute to reducing space heating and cooling energy use for thermal comfort in buildings.

Box 4.1 C40 cities: Leading by example

The C40 Cities Climate Leadership Group was established in 2005 as a global network of large cities that are developing and implementing policies and programmes that lead to measurable reductions in greenhouse gas (GHG) emissions and climate risks. The C40 network now consists of more than 75 megacities, representing more than 550 million people and roughly one-quarter of global GDP, which have undertaken more than 10 000 actions since 2005 to reduce urban emissions and climate risks.

Among these actions are several building performance measures to promote energy-efficient building designs and regulations that will facilitate an improved building market that values energy efficiency. Many cities have implemented measures to reduce energy consumption in municipal buildings, which account for an estimated one-third of C40 cities' building energy consumption. For instance, Paris, France, has committed to reducing energy consumption and CO_2 emissions in municipal buildings by 30% by 2020 compared with 2004 levels, including deep renovations of 600 public schools to reach a target of 65 gigawatt hours (GWh) of energy savings per year. 39 C40 cities in 2015 (compared with 10 in 2011) are now implementing building energy management systems in municipal buildings and facilities.

Other cities have introduced broader public programmes to improve energy efficiency in the entire local building stock, including both residential and commercial buildings. For example, Melbourne, Australia, implemented a series of both voluntary and mandatory building energy codes to support its target of being a carbon-neutral city by 2020. These measures include the 1 200 Buildings Program, which provides funding support to owners of commercial and non-residential buildings who commit to achieve at least a 38% improvement in energy efficiency.

Data reporting and benchmarking in commercial buildings have become increasingly popular among C40 cities, with 30 cities implementing this type of action in 2015, compared with just 10 cities in 2011. The C40 network is also helping cities to exchange information and share experiences to support action on improving building energy efficiency. This effort includes the C40 Municipal Building Efficiency network that was launched in 2014 to identify technologies and energy efficiency financing mechanisms for public buildings. Similar networks were created for private building energy efficiency and district energy systems.

To date, more than 2 215 actions have been taken by C40 cities for energy efficiency and emissions reduction in the buildings sector (C40 and ARUP, 2015). More information can be found online at www.c40.org.

4 Further information can be found in the IEA Policy Pathway *Energy Performance Certification of Buildings* (IEA, 2010a), *Monitoring, Verification and Enforcement* (IEA, 2010b) and *Modernising Building Energy Codes* (IEA, 2013c).

Cities are also often at the forefront of building energy efficiency, with some cities going beyond national energy policy measures and implementing innovative responses to energy and sustainability objectives. As the home to half the world's population and an estimated 80% of global gross domestic product (GDP), urban areas tend to be the first places to adopt new building technologies, from energy-efficient lighting and appliances to heat pumps and advanced district heat networks with integrated renewable energy. Greater support of local energy efficiency action, including developing the right policy and market measures to value innovation in urban buildings, can help to maximise the energy efficiency potential in the buildings sector.

Urban building variability and the effects of urbanisation

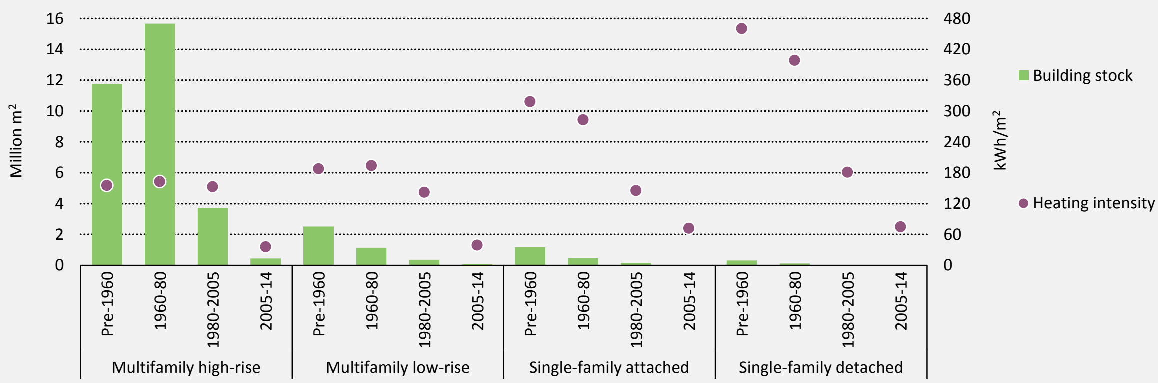
The physical characteristics and energy usage patterns of the global buildings sector are highly diverse, although several common building types exist in most urban areas. In the residential subsector, dense urban centres typically have multifamily, multistorey (i.e. greater than three storeys) buildings. Lower-density urban areas and peri-urban (suburban) areas more often have multifamily low-rise and single-family homes. Each residential building type can have very different demand for both heating and cooling, depending on local climate, vintage and material choice, while core energy loads for refrigeration, water heating, cooking and cleaning are typically tied more closely to the number of occupants.

Commercial and public services subsector building types similarly have large differences in energy consumption and performance intensities depending on the building type and purpose. The food service industry, hospitality industry, hospitals, shopping centres and office buildings with large glass facades often have high energy intensities, whereas warehouses, libraries, schools and general office buildings often have low or moderate energy intensities. Building design – for example, the choice of operable or inoperable windows with mechanical heating, ventilation and air-conditioning (HVAC) systems – and operations (e.g. control- or sensor-based variable temperature space conditioning in lieu of time-based conditioning) can also significantly affect building energy demand. Some modern buildings, even with advanced, energy-efficient technologies, can actually have very high energy intensities when compared with older, more traditional buildings as a result of design and building operations (IEA-TU, 2015).

Conducting more detailed analyses of building types and intensities, urban planners and policy makers can prioritise specific building stock segments for policy intervention. For example, one building segment in Turin (Italy) represents a large portion of that city's residential building stock and energy consumption (Figure 4.3).[5] Multifamily, high-rise buildings constructed prior to 1980 account for more than 70% of total residential floor area and roughly 70% of total energy consumption for space heating.[6] These buildings also have an average space heating energy intensity (final energy) above 150 kWh/m^2. Pursuing deep renovations and energy efficiency measures in these buildings would, therefore, offer substantial energy savings.

5 Residential buildings account for roughly 56% of the total number of buildings (ISTAT, 2015) and more than 40% of total final energy consumption in Turin (City of Turin, 2014).
6 Space heating accounts for more than 60% of residential energy consumption (Fracastoro and Serraino, 2009).

Figure 4.3 Building stock and heating intensity by type and vintage in Turin



Note: m^2 = square metre.
Source: Mutani, G. and G. Vicentini (2015), "Buildings' energy consumption, energy savings and the availability of renewable energy sources in urban contexts: The potential of GIS tools", *Journal of Civil Engineering and Architecture Research*, www.ethanpublishing.com/index.php?m=content&c=index&a=show&catid=230&id=579.

Key point *Data collection and analysis can help to identify key building stock segments that can be used to prioritise policy action and programme development in support of large energy savings.*

Global urbanisation to 2050 is likely to have important implications on building stock variations and energy consumption patterns. In developed countries, migration from rural or suburban areas (typically single-family homes) to denser urban areas (often attached or multifamily dwellings) could result in significant reductions in building energy consumption, because non-urban single-family homes often have much higher energy footprints per household or per person than multifamily dwellings (Table 4.1). This difference is partly because of larger floor areas in non-urban single-family homes as well as greater exterior surface area per dwelling (often referred to as the shape factor), both of which play an important role in household space heating demand. Conversely, urban multifamily buildings can be more energy-intensive for cooling loads (since they are denser, with more people and equipment per unit of floor area) and can have greater internal heat gain than a single-family house. However, because heating loads are generally far more intensive in temperate or colder regions than cooling loads in warmer regions, the net effect is that urbanisation (and urban densification) in many developed countries has a positive effect on overall thermal loads and energy consumption for heating and cooling.

In emerging economies and developing countries, urbanisation is likely to have a mixed effect on energy consumption and intensities in buildings in the coming decades because of the various effects of rural-to-urban migration on energy demand and fuel choice. Traditional use of biomass in rural areas (and even some urban areas) is still very common in many developing countries. In some countries, traditional use of biomass can even increase in some urban areas because of easier access (e.g. to charcoal) and greater affordability (in terms of share of household income).

Table 4.1 **Typical urban and non-urban household characteristics and energy intensities for select countries**

	United States		Sweden		China		India	
	Multi-family*	Single-family*	Multi-family*	Single-family*	Urban (average)	Rural (average)	Urban (average)	Rural (average)
Persons per household	1.9-2.3	2.5-2.8	1-2.3	1.6-2.6	2.8	3.9	4.6	4.9
Floor area per household (m^2)	79-102	101-231	45-84	120-220	76	144	47	54
Energy use (MWh/household)	14-22	20-31	11-14	19-30	6.6	16	7.9	9.2
Electricity use (MWh/household)	6.4-7.2	9.1-13.5	2.0-4.6	4.7-23**	2.2	1.0	1.4	0.7
Energy intensity (kWh/m^2)***	177-215	134-197	115-156	88-140	88	110	146	170
Energy use (MWh/person)	7-10	8-11	7-9.5	6.5-10	2.3	4.1	1.7	1.9

*Single-family and multifamily households are not explicitly urban or rural. Multifamily residential buildings are more likely to be in urban and suburban areas with increased density of households per building, often occurring as a region urbanises. Single-family households are also more likely to be rural or suburban, as is the case in the United States and Sweden. **Many single-family households in Sweden are heated directly using electricity. Many have installed air-to-air and geothermal heat pumps. Absent these technologies, household electricity use can be high. ***Total household energy use per m^2 does not accurately represent the effect of energy intensity differences in single- and multifamily homes, as water heating, cooking, appliances and other plug-load energy uses are typically tied to household occupancy.

Note: Energy intensities can vary significantly across residential building types, designs and locations and because of occupant behaviours. Typical energy consumption is reported as final energy.

Sources: United States: US DOE (2014), *Buildings Energy Data Book*, and US EIA (2009), *Residential Energy Consumption Survey*, elaborated by the International Energy Agency (IEA); Sweden: SEA (2013a), *Energistatistik för flerbostadshus (Energy Statistics for Multifamily Buildings) 2012*, and SEA (2013b), *Energistatistik för småhus (Energy Statistics for Detached Houses) 2012*, elaborated by IEA; China: TU (2014), *2014 Annual Report on China Building Energy Efficiency*, elaborated by IEA; India: Government of India (2012), *Census of India 2011*, elaborated by IEA.

While traditional use of biomass may still be common in some urban areas in developing countries, it often is strongly correlated to income and access to modern energy services and amenities (e.g. electricity networks and appliance ownership). Urbanisation, and increased access to energy networks and commercial fuels, is therefore likely to lead to reduced traditional use of biomass. Because the energy intensity of traditional use of biomass (e.g. for heating and cooking) is very high compared with the same activities performed using modern commercial fuels or even using clean cook stoves with solid biomass (IEA, 2013a), the net effect of rural populations moving to urban areas is expected to be a reduction in household biomass intensity.

At the same time, urbanisation, access to energy networks and the effect of increasing wealth will all likely increase household demand for energy services and activity. For instance, urban households in developing countries often use more lighting (in terms of hourly usage and lumens per m^2) than do rural households, because energy costs are typically a much smaller fraction of urban household income. Space heating and cooling demand and hot water usage also typically increase with urbanisation, since households have greater purchasing power and can afford greater comfort. Appliance ownership and usage similarly increase in urban areas in developing countries. Urban household energy intensities – in terms of use of modern commercial fuels – therefore are usually significantly higher than in rural households.

The net effect of urbanisation in developing countries – accounting for changes in energy behaviour, household purchasing power and shifts from traditional use of biomass to modern commercial fuels – will have a significant impact on buildings sector energy use and intensities as household demand for services and comfort in emerging markets continues to approach levels similar to developed countries. While rural-to-urban policy development goes beyond core building issues, policies that target high-efficiency building construction, efficient consumer choices and energy-efficient behaviour can also help to meet related development objectives (e.g. economic prosperity and improved health), because energy efficiency measures can have multiple benefits to society.[7]

Urban building energy demand

To assess the contribution of urban building energy demand and efficiency potential, global urban building energy consumption has been estimated across the residential and services subsectors and the major end uses (space heating and cooling, water heating, lighting, cooking, appliances and other equipment).[8] A general modelling methodology was used to distribute energy consumption by end use and fuel type to urban and non-urban buildings. This methodology uses best available information in IEA datasets and the IEA Energy Technology and Policy buildings model. Secondary analysis was applied where quality data are not available.[9]

Urban building energy drivers

Historically, several factors have played a significant role in energy demand in the buildings sector, including population, economic activity (as expressed by GDP), buildings sector size (e.g. floor area and number of households), building energy policies and other factors, such as climate and energy prices (IEA-IPEEC, 2015). The extent to which each factor contributes to building energy consumption differs from country to country, within countries, and across social, economic, geographic and demographic characteristics.

The global building stock accounted for an estimated 212 billion m^2 in 2013, of which more than 80% was residential floor area across as many as 2 billion households. Urban buildings accounted for an estimated 126 billion m^2 (or roughly 60% of global building floor area), including nearly 31 billion m^2 of floor area in the services subsector (84% of total services floor area) and 1.2 billion households (60% of the global total, or 95 billion m^2).

By 2050, urban building floor area is expected to double to 254 billion m^2, with more than 75% of expected growth coming from countries that are not members of the Organisation of Economic Co-operation and Development (OECD) (Table 4.2). This growth is largely the result of urbanisation in non-OECD countries (with total urban population nearly doubling in those countries). The growth is also because of expected increases in average household floor area as incomes in urban areas continue to rise. Services floor area in non-OECD countries likewise doubles between 2013 and 2050. In OECD member countries, urban floor area increases by 50% over 2013 levels. This increase is partly owing to continued urbanisation as well as continued growth of urban services activity (with services floor area in those countries growing 55% between 2013 and 2050).

7 Additional information on the benefits of energy efficiency measures can be found in the IEA publication *Capturing the Multiple Benefits of Energy Efficiency* (IEA, 2015b).

8 The high diversity and variability of the global building stock – along with the considerable need for improved data on building energy characteristics and performances – make it difficult to accurately assess urban building energy consumption. Urban boundary definitions (i.e. what is considered urban, peri-urban and rural) also make it challenging to distinguish global urban building energy consumption. Country definitions vary considerably (see Chapter 3), and building types and energy consumption patterns can vary significantly across different urban forms.

9 Additional information on the assumptions and process used to estimate global urban building energy can be found in Annex E online; see www.iea.org/etp/etp2016/annexes.

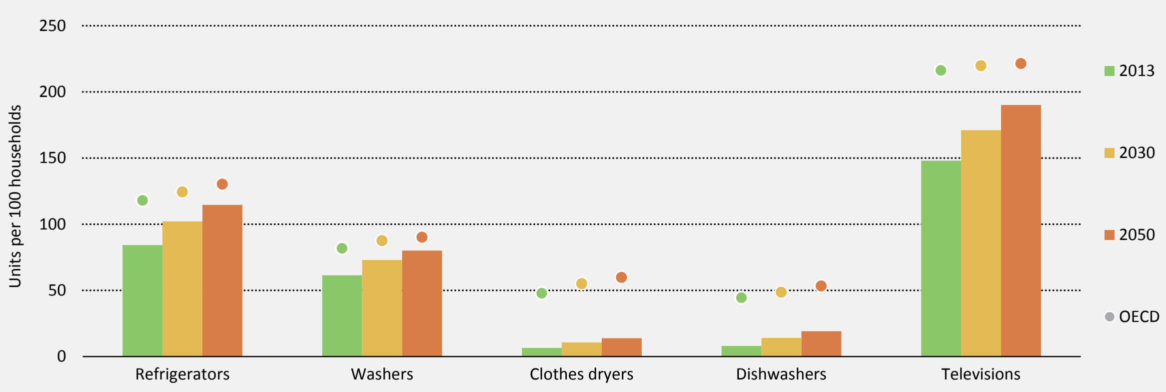
Table 4.2 Drivers for energy consumption in urban buildings to 2050

	OECD			Non-OECD		
	2013	2030	2050	2013	2030	2050
Population (million)	1 009.4	1 139.5	1 237.1	2 754.5	3 871	5 041.7
GDP (USD billion)	41 642	60 599	86 067	44 235	102 751	198 200
Households (million)	390.7	452.8	494.3	810.0	1 266.3	1 736.7
Occupancy (persons per household)	2.6	2.5	2.5	3.4	3.1	2.9
Average household size (m^2)	104.6	113.1	120.6	67.2	77.7	81.7
Residential floor area (billion m^2)	40.9	51.2	59.6	54.4	98.3	141.9
Residential floor area per capita (m^2)	40.5	44.9	48.2	19.8	25.4	28.2
Services floor area (billion m^2)	18.7	23.8	29.0	12.1	17.6	23.3

Note: GDP expressed in 2014 USD at purchasing power parity; further description of buildings sector drivers for urban energy estimates can be found in Annex E online; see www.iea.org/etp/etp2016/annexes.
Sources: Population: UN DESA (2014), *World Urbanisation Prospects: The 2014 Revision*. GDP: urban GDP was estimated for 189 countries from 2013 to 2050 using McKinsey (2015), *McKinsey Global Institute Cityscope v2.55*; IMF (2015), *World Economic Outlook Database, April 2015*, www.imf.org/external/pubs/ft/weo/2015/01/weodata/index.aspx; and IEA (2015d), *World Energy Outlook*.

Urbanisation and increasing wealth in non-OECD countries will also contribute to a rapid growth in appliance ownership. In many developing countries, ownership levels for large appliances (e.g. refrigerators and clothes washers) and other household plug loads (e.g. computers and televisions) are still low, with significant potential for growth. For example, in India less than 8% of households in rural areas and only around 40% of urban households had a refrigerator in 2010 (Prayas, 2012). In 2013, still less than 10% of rural households in India had a refrigerator, while urban ownership grew to 50% (IEA, 2015c). In China, less than 10% of urban households and practically no rural households owned a computer in 2000; by 2012, nearly 95% of urban households in China owned a computer, while still less than a quarter of rural households owned one (NBS, 2014). As household incomes continue to rise in non-OECD countries, especially in urban areas, appliance ownership levels are, therefore, likely to increase rapidly (Figure 4.4).

Figure 4.4 Estimated urban ownership levels to 2050 in non-OECD countries



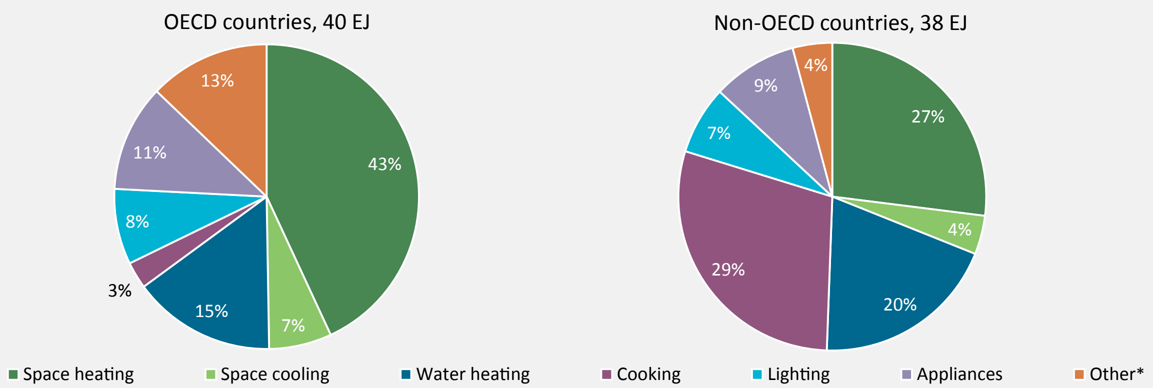
Note: Ownership levels vary considerably across non-OECD countries relative to household wealth (GDP per household).

Key point *Appliance sales to 2050 are expected to surge in urban areas in developing countries as household income and appliance ownership levels continue to increase.*

Energy demand outlooks and opportunities to 2050

Total energy consumption in urban buildings accounted for an estimated 78 EJ in 2013, or more than 60% of total building energy consumption that year. Urban buildings in non-OECD countries consumed nearly as much as urban buildings in OECD countries, although stark differences exist in energy demand across the building end uses (Figure 4.5). For instance, urban space heating energy use is roughly 65% greater in OECD countries, because non-OECD countries are typically in far warmer climates with smaller heating loads and often with different temperature comfort expectations. Conversely, energy consumption for water heating and cooking is far more important in non-OECD countries, partly because of smaller space heating and (for the time being) smaller cooling loads. Also, traditional use of biomass, even in urban areas, is still considerable in many developing countries. When biomass is excluded, global urban buildings accounted for nearly three-quarters of total building energy use in 2013.

Figure 4.5 Urban building final energy estimates by end use, 2013



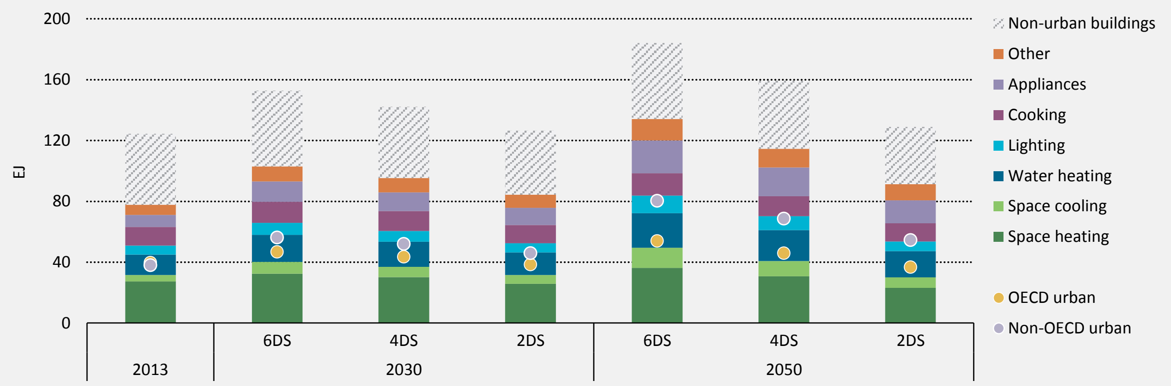
* "Other" refers to other building equipment (e.g. everything from refrigerated display cabinets to electric motors, information technology networks and x-ray machines) not accounted for in the six principal building end uses.
Source: Calculations derived with IEA (2015a), *IEA World Energy Statistics and Balances* (database), http://dx.doi.org/10.1787/data-00512-en.

Key point *Globally, space heating demand in urban areas is the single-largest building end use, while cooking and water heating are still a large share of energy demand in developing countries.*

Stark contrasts also appear in fuel shares and average urban building energy use per person between OECD and non-OECD countries, even as urban energy demand in developing countries continues to grow at a rapid pace. In OECD countries, electricity and natural gas accounted for more than 80% of total urban building energy consumption in 2013. Average urban building energy use was roughly 11 MWh per person. By contrast, in non-OECD countries, electricity and natural gas use accounted for only 40% of urban building energy use, while biomass consumption was nearly 30%. Average urban building energy use in non-OECD countries was still less than 4 MWh per person, although some of this lower figure can be explained by differences in building energy requirements (e.g. climatic conditions that require less space heating) and lower appliance and equipment ownership.

Under the 6DS, urban building energy consumption reaches 134 EJ in 2050 (roughly 73% of total building energy consumption in 2050). This projection means that nearly 95% of expected energy growth in global buildings is likely to occur in urban areas. Urban building energy consumption in 2050 under the 6DS more than doubles over 2013 levels in non-OECD countries as demand for energy services and comfort continue to increase, along with urban population growth. By contrast, urban building energy use in OECD member countries continues to increase marginally by less than 1% per year to 2050 under the 6DS (Figure 4.6).

Figure 4.6 **Urban building final energy consumption and savings scenarios by end use**



Key point *Urban building final energy consumption could increase by as much as 70% over 2013 levels under the 6DS, with urban building energy demand more than doubling in non-OECD countries.*

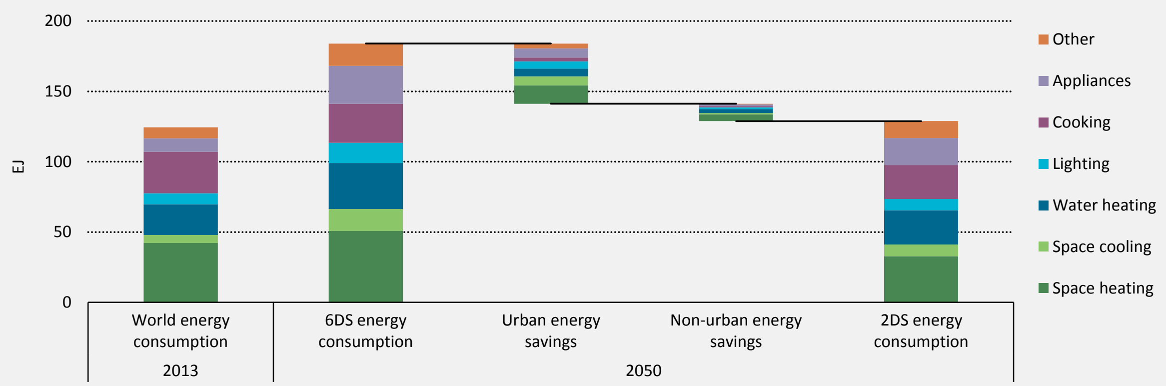
Growing household wealth, paired with continued growth in demand for comfort, contributes to significant growth in energy consumption for urban building space cooling, which globally increases more than three times over 2013 levels under the 6DS. In rapidly emerging, warm-climate, non-OECD countries (e.g. India, Indonesia and Mexico), urban space cooling demand increases as much as five- to tenfold over 2013 levels by 2050. Global urban energy consumption for appliances and other small residential plug loads (e.g. computers and small electronic devices) similarly surges in non-OECD countries as household wealth and demand for energy services increases. Globally, urban appliances and other plug-load energy use grows by more than 175% from 2013 to 2050 in the 6DS, and nearly 350% in non-OECD countries during the same period.

Under the 4DS, global urban building energy consumption grows to 114 EJ in 2050 (15% lower than the 6DS, but still roughly 50% higher than 2013) as the result of increased energy efficiency measures across end-use technologies (e.g. heating and cooling equipment, lighting and appliances) and increasing shifts away from traditional use of biomass for water heating and cooking in residential buildings. Improved adoption and enforcement of building energy codes for new building construction also help to curb space heating and cooling demand growth, especially in non-OECD countries. However, those improvements are still not enough to offset the significant growth in building floor area additions to 2050 and the increasing demand for thermal comfort in developing countries. Deep energy renovations of existing buildings remain limited under the 4DS with insufficient policy measures to address the necessary market uptake and cost-effectiveness of deep building energy renovation measures (i.e. economies of scale).

Under the 2DS, global urban building energy consumption decreases by 30% compared with the 6DS in 2050, accounting for more than 75% of global building energy reductions

(Figure 4.7). This decline is due to deep energy renovations of existing buildings, paired with very-low-energy new building construction and high-efficiency equipment purchases, reducing overall space heating and cooling energy consumption. Demand for energy services and comfort in developing countries continues to increase in both the 6DS and the 2DS, but more rigorous and enforceable building energy codes for new construction, along with energy efficiency and fuel-switching measures (e.g. from inefficient use of biomass to solar thermal water heating), help to meet that demand with lower overall energy consumption under the 2DS.

Figure 4.7 Global final energy savings by end use, 6DS to 2DS



Key point *Urban buildings account for more than 75% of global building final energy savings in 2050, with space heating and cooling demand reductions accounting for roughly 40% of urban building energy savings.*

Globally, urban space heating and space cooling demand under the 2DS is reduced by 40% compared with the 6DS, accounting for 45% of total urban energy savings in 2050. Building envelope improvements account for nearly 80% of urban building space heating and cooling savings. Lighting and appliance energy use is reduced by 35% as a result of performance standards and increased uptake of high-efficiency products, and cooking is reduced by nearly 20% through energy-efficient equipment (e.g. clean cook stoves) and greater shifts away from traditional use of biomass. Urban water heating energy use decreases by 25% in 2050 compared with the 6DS because of energy efficiency measures (e.g. mandatory condensing and heat pump water heaters) and considerable growth of solar thermal collectors.[10]

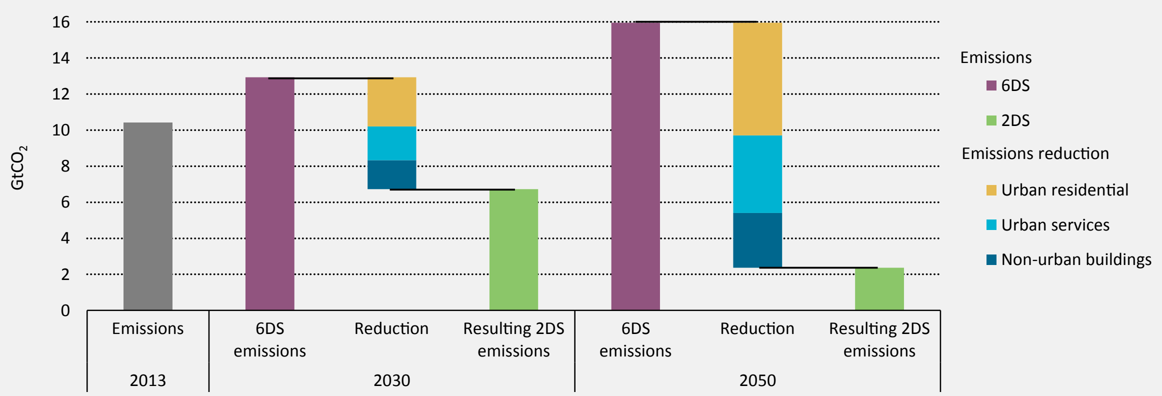
Global electricity consumption in 2050 under the 2DS decreases by 33% compared with the 6DS. Energy efficiency measures and the consequent electricity savings would allow for greater access to affordable electricity, especially in developing countries, and the large uptake of very efficient technologies (e.g. heat pump technologies for space heating, space cooling and water heating) could achieve that increased access while still consuming less electricity than in the 6DS. Renewable technologies, such as solar thermal water heaters, would also allow for increased access to energy services and improved comfort without increasing commercial electricity demand. Total urban solar thermal consumption (for space heating and water heating) increases more than 1 000% over 2013 levels under the 2DS,

10 While solar photovoltaic (PV) can be placed on buildings, it is accounted for within the energy supply mix under the *ETP* modelling framework. Additional information on solar PV opportunities in urban areas can be found in Chapter 6.

while fossil fuel consumption (i.e. coal, oil and natural gas) in urban buildings decreases by 50% in 2050 compared with the 6DS.

Under the 6DS, urban CO_2 emissions increase from 7.5 $GtCO_2$ in 2013 to nearly 12 $GtCO_2$ in 2050. Building energy efficiency measures, including equipment efficiency and improvements in the thermal envelope of buildings, and fuel switching in the 2DS lead to an 85% reduction of total CO_2 emissions in urban buildings in 2050 compared with the 6DS. Direct emissions (from the combustion of fossil fuels) decrease by 50% in 2050 compared with the 6DS, while indirect emissions (from upstream generation of electricity and commercial heat) decrease by 93%. Nearly 65% of 2DS urban CO_2 reduction comes from the residential subsector, which represents half of global buildings sector emissions reduction to 2050. Overall, urban buildings account for more than three-quarters of total buildings sector emissions reduction to 2050 (Figure 4.8).

Figure 4.8 **CO_2 emissions reduction (direct and indirect) in urban buildings, 6DS to 2DS**



Key point *Urban building CO_2 emissions in the 2DS are 85% less than 6DS levels in 2050 as a result of energy efficiency measures, paired with decarbonisation of electricity and commercial heat production.*

Urban building energy efficiency measures have considerable importance in global CO_2 emissions when the impact of buildings energy consumption on power generation is considered. Urban buildings are estimated to have accounted for nearly 80% of total building electricity and commercial heat consumption in 2013, and more than 80% of total global building electricity growth to 2050 is expected to come from urban buildings.

While the global buildings sector constituted only about 8% of (direct) energy-related CO_2 emissions in 2013, more than half of global electricity and commercial heat went to buildings that year, making it responsible for roughly 7 $GtCO_2$ of upstream CO_2 emissions (or roughly 30% of total global CO_2 emissions [direct + indirect]). Energy efficiency in urban areas, therefore, not only contributes to reducing overall building electricity and commercial heat demand, but also plays an important part in supporting decarbonisation of the power sector. Improved efficiency and reduced building electricity and heat demand will allow for a more efficient, more resilient and lower carbon grid.

Energy efficiency and fuel switching in urban buildings can also contribute to improved living conditions (e.g. improved thermal comfort) and better air quality in cities. While local pollution and quality of life are difficult to quantify within the *ETP* global modelling framework, it is well documented that the continued use of fossil fuels and also traditional use of biomass can have a considerable impact on local air quality. Many cities across the globe have identified air quality as a major public health concern, and energy efficiency in buildings, paired with a decline in fossil fuel consumption in buildings, contributes to reductions in local air pollution (Box 4.2).

Box 4.2 Local air pollution and urban buildings in China

Air pollution in China's cities, notably from respirable particulate matter (PM_{10}) and fine particles ($PM_{2.5}$), is a serious issue that has been identified by the Chinese government as a priority area of concern. While transport, industry and power generation (notably using coal) are the major sources of local air pollutants in most Chinese cities, the buildings sector is also largely responsible for local air quality, both because of direct consumption of coal and other fossil fuels and also because buildings in north urban China consume considerable amounts of commercial heat from China's important district heating network, fuelled mostly by coal.

Building energy consumption and emissions have been highlighted as a key priority for the Chinese government, which recognised the important role of the buildings sector on air pollution prevention and control in its *Air Pollution Prevention and Control Act Plan* (State Council, 2013a). The plan set the goal of improving overall national air quality, including measures to proactively develop green buildings and district heat reform in urban China. Specifically, the plan considers detailed measures to: adopt green building standards in public buildings and indemnificatory housing (rent-controlled or price-controlled housing options provided by the government for low- and middle-income families); implement mandatory energy-saving standards in new buildings; promote the utilisation of low-carbon, energy-efficient technologies and equipment (e.g. solar water heating, heat pumps and building-integrated solar PV); accelerate the push for heating metering and energy efficiency renovation in existing residential buildings in north urban China; and accelerate the development and refurbishment of the district heat supply network.

Since 2013, the Chinese government has developed additional strategies in line with the *Air Pollution Prevention and Control Act Plan* and the broader *12th Five-Year Energy Development Plan* (State Council, 2013b), including the *Green Building Action Plan* (State Council, 2013c) and the 2014 *National Plan on New Urbanisation for 2014 to 2020* (State Council, 2014), which both set forth goals for reducing energy consumption and emissions from the buildings sector (IEA-TU, 2015).

Energy technology priorities, policies and benefits for urban buildings

The energy savings potential in buildings is enormous, and currently only around 30% of total energy consumption in the buildings sector is covered by energy efficiency regulations (IEA, 2015d). While most building technologies and policies to achieve more efficient buildings are not unique to urban environments, numerous technology solutions are available today that can significantly reduce urban building energy consumption.[11] These solutions include advanced lighting (e.g. light-emitting diodes [LEDs])[12], water heating technologies (e.g. instantaneous condensing gas water heaters, heat pump water heaters and solar

11 Additional information on building technologies and policies can be found in the IEA's *Transition to Sustainable Buildings: Strategies and Opportunities to 2050* (IEA, 2013a).

12 While not considered in this chapter, street lighting can be a large energy consumer in urban areas. Energy-efficient LED lighting for street lighting applications is rapidly increasing in many urban areas and can have additional benefits, such as improved lighting quality and coverage. Additional information can be found in Chapter 7.

thermal collectors) and advanced building envelope materials.[13] Geothermal technologies in new building construction (including integration of heat exchangers in structural components, such as building foundations) can also deliver significant energy savings using local resources (e.g. lakes, rivers, oceans and the ground).

Some priority technologies for the buildings sector may have limited opportunities in the urban built environment. In particular, solar PV and solar thermal market adoption may be limited in certain urban areas as a result of building densities and space constraints, although these technologies could still be used outside the city as part of an integrated, efficient energy network (see Chapter 6). While solar thermal is a critical low-carbon technology, there may be insufficient surface area in some cities to provide enough heat to satisfy water heating or space heating demand in larger buildings (e.g. multifamily residential buildings, hospitals and hotels) or high-density building clusters. Building shading by the surrounding built environment in higher-density urban areas may also limit adoption of solar technology applications. Integrated facade solar thermal systems are a promising option, but further development is still needed to make these systems cost-effective and technically viable across various applications.

Urban areas can play a critical part in curtailing the energy consumption of the world's building stock through policies that increase adoption of energy efficiency measures and advanced building technologies. The most critical priority should be to address space heating and cooling demand through building envelope technologies and efficient heating and cooling equipment. Many cities are already leading in this area through energy efficiency measures in public buildings and through building technology and energy efficiency awareness programmes, which can be more targeted than national energy policy. However, significant effort is still needed to develop and adopt robust, enforceable and adaptable advanced building energy codes[14] across all regions as well as to enable and pursue a long-term global strategy for deep energy renovation[15] in existing buildings (IEA, 2013a).

Typically, key building construction and energy code policies are most successful when adopted in harmonisation across a country or region and then locally enforced by cities. Local governments often have building regulatory, planning and zoning functions, as well as other important municipal levers, such as taxation and local loans. They also can help to achieve greater levels of education across stakeholders to help administer effective building policies. From a national and global public policy perspective, engaging cities can improve the effectiveness of building policies as a result of their large economies of scale and the potential replicability of programmes. For example, the European Energy Award (EEA) supports local authorities in establishing and implementing effective energy and climate policy measures using a centralised quality management and certification system. More than 1 300 municipalities in Europe now participate in the programme across a variety of topical areas and initiatives.[16]

National policies have substantial influence to enable local decision makers to pursue appropriate urban planning and energy efficiency measures. This influence includes the use of national land-use planning frameworks, fiscal policies (e.g. tax incentives, grants and subsidies, housing loans and third-party financing), quality management systems (including advisors and auditors) and capacity-building programmes to provide direction and empower local planning and policy design[17]. These types of national or regional energy

13 More information on building envelope technologies, including advanced building envelope components, can be found in the IEA Technology Roadmap *Energy Efficient Building Envelopes* (IEA, 2013b).

14 See IEA Policy Pathway *Modernising Building Energy Codes* (IEA, 2013c) for more information.

15 The Global Buildings Performance Network defines deep renovations as actions that achieve building performance levels that are not more than 60 kWh/m^2 per year for all building code loads (i.e. space heating and cooling, water heating and installed lighting) (GBPN, 2013).

16 For more information, visit the EEA website at www.european-energy-award.org/.

17 Additional information on fiscal tools for building energy efficiency can be found in the Buildings Performance Institute Europe report *Energy Efficiency Policies in Buildings – The Use of Financial Instruments at Member State Level* (BPIE, 2012).

efficiency frameworks (e.g. ENERGY STAR in the United States) also provide transparent, consistent and science-based approaches for local policy makers and stakeholders who may not have the resources or capacity to design their own standards or labelling programmes. By providing strong support to cities, national governments can, therefore, help deliver sustainable energy transitions in urban buildings, including the use of adaptive measures and targets, while also achieving national energy and climate policy targets (see Chapter 7).

One critical policy area that has had broad success in the buildings sector is the promotion and regulation of more efficient building energy-consuming equipment (e.g. appliances, lighting and heating equipment) through labelling and MEPS. These measures are typically pursued at a national level, although some cities have initiated their own policy programmes that support or mandate purchases of energy-efficient equipment. For instance, Cape Town, South Africa, implemented mandatory lighting and appliance efficiency policies in 2014 to reduce growth in rising electricity demand (City of Cape Town, 2015).

One particular area of policy interest in the global buildings sector is to improve data and understanding of actual building energy performance, which is needed to develop and refine both national and local buildings sector policy priorities. Data, and a more acute sense of local building energy needs and opportunities, are valuable tools that city and municipal authorities can use to shape policy decisions and prioritise energy efficiency efforts. This information can also help cities to target the right stakeholders (e.g. building operators and local construction companies) to increase adoption of energy-efficient technologies.

Several cities are already leading in this area with mandatory policies that require energy consumption and performance disclosure reporting (IMT, 2015). Some cities – for instance, the city of Boulder, Colorado, in the United States – are even taking this a step further and requiring certain building types to comply with local MEPS as part of the building rating and reporting programme (City of Boulder, 2015). However, many cities do not have the resources or capacity to implement these types of programmes. National support of local action in this area would be beneficial to both urban areas and national policy makers in improving understanding of buildings sector performance and establishing more effective, targeted building energy policies.

Despite the important role urban authorities can play in meeting building energy efficiency and emissions objectives, local policy makers and building actors do not always consider building actions with respect to CO_2 emissions reduction or energy efficiency design. Instead, urban policies often consider other important building issues such as energy poverty, affordable housing, building safety and working conditions within the built environment. Yet energy efficiency measures in buildings can add essential local value through job creation, lower energy bills, improved air quality and even improved quality of living (e.g. through improved thermal comfort). Because buildings sector investments and economic prosperity are closely linked, implementation of energy efficiency measures in the urban buildings sector can lead to important multiple benefits for local economies, while reducing total building energy consumption and CO_2 emissions (Box 4.3).

Incorporating multiple benefits of energy efficiency into local planning and policy design and tapping into the enormous energy-savings potential in urban buildings will require both support and direction from national policy frameworks. While many cities are already acting on important energy-related building issues, barriers to achieving the potential scale of urban sustainable energy actions in the buildings sector still often arise. These barriers frequently include jurisdictional rights and boundaries (i.e. lack of authority to implement certain policies), financial constraints (e.g. lack of capacity to raise or leverage funds for energy efficiency programmes) and other capacity-related issues (e.g. institutional knowledge of advanced building technologies).

Box 4.3 Building energy efficiency measures: Multiple benefits for local communities

Energy efficiency has been the primary factor in reducing energy consumption in IEA countries over the last 25 years. Avoided expenditures in IEA countries resulting from energy efficiency investments during that period were valued at USD 5.7 trillion (IEA, 2015e). Globally, significant investments in energy efficiency continue to rise, with energy efficiency now considered a "first fuel" in terms of effective tools for achieving energy conservation goals (IEA, 2015b). The broader economic, social and environmental benefits of energy efficiency investments are also increasingly recognised in policy decision making, alongside the conventional benefits of reduced energy demand and lower GHG emissions. This broader perspective is in part because of the variety of policy issues that can be supported by energy efficiency.

Buildings present a significant opportunity for addressing multiple policy goals via energy efficiency improvements. Building energy efficiency investments can contribute to economic development by boosting productive GDP growth, creating net employment and reducing the amount of generation assets needed to meet peak demand (Washah, Stenning and Goodman, 2014; Mount and Benton, 2015). Investments in energy efficiency are also pursued as a means of addressing energy affordability in urban areas, because making energy services less expensive and addressing energy poverty in cities can result in direct public health benefits (e.g. fewer premature deaths and reductions in respiratory infections), which further improve the cost-benefit case for energy efficiency investment (Wilkinson et al., 2009).

Evidence of health co-benefits can similarly be used to justify revenue sharing between public budgets, with empirical studies in the United Kingdom showing as much as 42% of building energy renovation costs being recouped through co-benefits on health budgets (Liddell, 2008). Energy efficiency improvements can also be seen as a business diversification activity for energy suppliers, offering new services while reducing the overall cost of services to citizens (e.g. as an energy service company) (Hall and Roelich, forthcoming).

The increased recognition of the multiple benefits of energy efficiency has resulted in a variety of approaches to their assessment within local policy decision making. Several IEA member countries (e.g. Germany and the United Kingdom) already incorporate net employment benefits from building energy renovations in their policy assessment processes. For instance, the CO_2-Building Rehabilitation Programme in Germany can be seen as an example of an energy efficiency investment programme used as a means of economic stimulus, to create jobs and boost economic growth (Rosenow et al., 2013). The influence of energy efficiency on economic growth, however, is not regularly featured in policy assessments in most countries.

Health and well-being benefits are increasingly connected with energy efficiency investments in buildings. Considerable disparity exists, however, between practices of accounting for these impacts in policy assessments. For example, the Warm Up New Zealand programme, where health and well-being outcomes made up the majority of recorded benefits (Motu, 2015), contrasts with policy assessment in the United Kingdom, where evidence of health and well-being benefits is provided, but no attempt is made at their quantification. No impact is consequently included on the energy efficiency policy's net present value assessment in the United Kingdom.

As the recognition of the multiple benefits of energy efficiency grows, addressing disparity between the levels of recognition shown by different cities and countries will help to add universal value to multiple benefits and allow their value to be integrated in building energy policy. Continued efforts are needed to raise the value of local energy efficiency measures in meeting multiple policy objectives for local decision makers. Best-case examples of where the benefits from energy efficiency policy have been recognised, and how they have been accounted for, can make an important contribution to justification of continued investment in energy efficiency in buildings. More broadly, international co-operation and experience sharing across cities can help to encourage the incorporation of energy efficiency in local policy design.

Note: Niall Kerr and Stephen Hall (both University of Leeds) provided substantive input to Box 4.3.

Reducing urban building heating and cooling energy consumption

Space heating and cooling currently account for around 40% of global building energy consumption and are a critical area of needed action in the buildings sector. Several factors influence building thermal demand, including climate, urban form and design, building orientation and shape profile, technology and material choices, and occupant behaviour. While variations in thermal energy demand across the global building stock may not be completely understood, policy support and building energy codes are needed everywhere to transform the building market and achieve an energy-efficient, low-energy buildings sector.

Reduced heating and cooling demand in buildings has been well documented in most mature markets using energy-efficient heating and cooling equipment and widely available, cost-effective building insulation, windows, doors, air sealing, improved distribution systems, and energy or heat recovery equipment (e.g. ventilation heat exchangers and exhaust air heat pumps). Reducing energy consumption to meet heating and cooling demand reduction is generally easier to achieve in new construction, although deep energy renovations in existing buildings in cold climates have achieved heating performance loads of 40 kWh/m^2 to 60 kWh/m^2 (compared with typical loads of 90 kWh/m^2 to 150 kWh/m^2 or higher) using cost-effective technologies. Other building deep renovation projects have shown that achieving very low heating loads in the range of 15 kWh/m^2 to 25 kWh/m^2 (more typical of nZEBs or *passivhaus* standards) is technically possible. However, these performance levels are not always cost-effective, and more research and development, market conditioning and product promotion are needed to advance this field (IEA, 2013b).

New construction, especially in emerging markets, provides important opportunities to reduce heating and cooling loads. Measures can include proper building orientation to the sun and designing the shape profile of the building to reduce thermal loads. Building codes are widely accepted to be the most effective policy instrument to influence new construction, although the effectiveness of building energy codes depends on the level of compliance, which typically requires monitoring, verification and enforcement. Urban areas, through permitting and local enforcement of construction and building energy codes, can play a critical part in achieving reduced thermal demand in buildings.

Cities can also help to transform building construction markets through local policy support and urban planning authorities (e.g. zoning and permitting) to guide them towards high-performance, energy-efficient buildings. This role includes working with local stakeholders to optimise building design that takes into account prevailing climatic conditions, greater passive design (including passive ventilation and solar heating contributions) and advanced facades that harvest natural daylight while reducing cooling loads. Local demonstration projects, including deep energy renovations in public buildings, can also be used as education tools and market drivers to encourage uptake of energy-efficient technologies and building practices in cities.

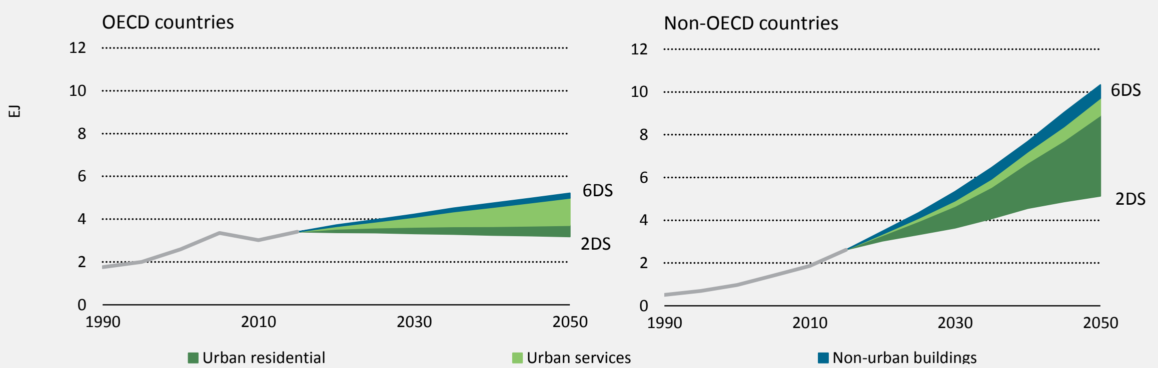
Another important part that urban areas can play in achieving low heating and cooling energy demand in buildings is through raising awareness with local consumers and building operators to address energy-efficient technology and behaviour in buildings. Consumer choices, behaviour and building operation can lead to significant energy consumption differences in any region of the world. For instance, in China, studies have shown that occupant behaviour and building operations can vary energy consumption between two- and sixfold in residential households and between two- and tenfold in office buildings (Zhang et al., 2010). The policy effort needed to achieve reduced urban building thermal energy demand, therefore, goes beyond construction and should include the operation of buildings, including advanced energy management tools and overall education and training for building operators and occupants.

Growing cooling demand in urban buildings

Global building cooling demand is increasing rapidly, especially in hot, humid climates in emerging markets. Beyond climate, cooling demand is also dependent on internal heat loads (e.g. from occupancy and equipment), on architectural and material choice, and on the size and design of the building (where natural cooling may not be possible because of issues such as building depth). Dense urban environments with large, multistorey buildings – including the increasing choice of glass facades in commercial and services buildings – are therefore ripe for growth in space cooling demand in most developing regions. Cities can also be significantly hotter than surrounding areas as a result of urban heat island effects.

Without concerted effort to reduce cooling energy demand in buildings through energy-efficient envelopes and cooling equipment, global building cooling energy consumption will continue to grow rapidly to 2050, especially in non-OECD countries, where more than 80% of expected space cooling growth is expected to occur (Figure 4.9). Urban areas, where the greatest growth in household demand for energy services and comfort will happen, are responsible for nearly 90% of expected global growth in cooling demand under the 6DS and likewise account for 85% of global cooling energy savings under the 2DS.

Figure 4.9 Cooling energy demand and savings, 6DS to 2DS



Key point *Building envelope and energy efficiency improvements would lead to a 50% reduction in global urban building cooling consumption in 2050 under the 2DS.*

In OECD countries, a significant share of space cooling loads and savings potential comes from the services subsector (because of higher use of mechanical HVAC systems in commercial and services buildings, relative to lesser need for space cooling in many residential buildings). In non-OECD countries, residential building space cooling energy consumption is likely to increase dramatically as household demand for thermal comfort increases in hot climates. With more than 900 million new households expected by 2050 in urban areas in non-OECD countries, these countries will need to implement more rigorous and enforceable building energy codes that reduce thermal demand intensities using a wide array of efficient building envelope and equipment technologies. Globally, similar actions are also needed to address thermal loads in services buildings, starting first with aggressive building energy codes for new construction, as well as deep renovation programmes for existing services buildings.

The first priority in building design and policy development should be to enable the reduced need for cooling, where the use of innovative technologies and building envelope design can actually avoid the need for interior conditioning (IEA, 2013b). In warm climates, new construction and building renovations should incorporate reflective surfaces (including cool roofs and low-emissivity [low-e] glass windows with spectrally selective coatings tailored to reject the sun's energy, building orientation and exterior shading). Natural and night-time ventilation strategies can also be applied in some climates, and reflective roadways and pavements (i.e. high albedo effect) near buildings can help to reduce average urban temperatures, which, in turn, reduces air-conditioning loads in buildings (LBNL, 2013).

Efficient cooling equipment is also of importance, although it should be a secondary priority after efficient building site and envelope design. Advanced chillers exist in many markets, and geothermal systems – typically in combination with heat pumps – can offer high performances for large individual buildings, for a cluster of smaller buildings or for district cooling networks. District cooling can also take advantage of urban building densities and economies of scale to achieve high operating efficiencies using numerous sources to produce chilled water. These sources can include the use of natural cooling sources (e.g. rivers, lakes, the ocean and other geothermal sources), renewable energy sources, and even off-peak and seasonal cooling generation (e.g. through ice storage or geothermal storage) that can help level out electricity demand and lower space cooling costs.[18] For example, the city of Chicago in the United States has the world's longest district cooling network (around 13 trench kilometres). The system delivers chilled water to more than 4.4 million m^2 of building space using five interconnected plants based on ice-storage technology (Enwave Chicago, 2015).

Beyond the energy-saving benefits provided by the large-scale, flexible, chilled water production process, district cooling networks can provide numerous benefits to buildings served, including lower capital costs, less fresh water used for cooling towers and chillers, and reduced floor area needed for mechanical equipment (often on the roof, where solar systems or green roofs could be installed). District cooling networks also provide benefits to the local utility grid by reducing electricity demand in buildings during peak cooling periods.

Efficient building envelope technologies

Globally, awareness of the importance of insulation in buildings is increasing, even if continued work is needed to improve knowledge of the right levels of insulation and to achieve better installation practices. By contrast, the important role of efficient windows and air sealing in building envelopes still needs to be elevated in building policy development and construction practices, especially in developing countries, where site-built windows with minimal quality control can negatively affect the long-term performance of buildings.

In most urban areas, multifamily residential buildings are a major building type with significant thermal loads. While these buildings often have much lower heat load requirements than single-family buildings (because exterior surface represents a smaller portion of each apartment), the glazing area (i.e. windows) within the thermal envelope represents a much greater portion (i.e. greater window-to-wall ratio). For example, typical window-to-wall ratios for single-family buildings may be 12% to 15%, whereas some apartments have ratios that might be as high as 60% or more. Installing more efficient

18 Natural cooling can also be used in cooling-assisted applications (i.e. in support of normal cooling processes) to improve district cooling efficiencies. For instance, the Climespace district energy network in Paris, France, uses natural cooling from the Seine River to augment operating efficiencies of its cooling production. Since natural cooling was applied in 2009, the average coefficient of performance of the plant chillers increased by more than 30% (IEA, 2014).

windows can, therefore, have a dramatic impact on heating and cooling demand, especially in emerging markets where the majority of installed windows are not efficient (i.e. low thermal performance) (Box 4.4).

Box 4.4

Technology roadmap: Energy-efficient building envelope technologies

The IEA released a technology roadmap, *Energy Efficient Building Envelopes*, in 2013, looking at critical and emerging technologies that improve the thermal load in buildings (IEA, 2013b). The roadmap also detailed the investment, policies, regulations and actions necessary to advance and popularise building envelope technologies in both new and existing structures.

Globally, one critical technology to improve window performance and building energy demand is low-e glass coatings. Low-e coatings act as radiant barriers that reduce heat loss in winter and heat gain in summer. They also have varying optical properties that allow either high or low solar heat gain, tailored to heating- or cooling-dominated climates. Low-e coatings reduce heat loss through windows by 33% to 40%, and can reduce heat gain from the sun by over 50%.

Another important window technology area is solar control, which can be used to reject as much heat as possible while transmitting high levels of visible light. This technology includes manual or automated exterior shading, solar glazing (e.g. window films) and dynamic glazing technologies (e.g. electrochromic glazing) that can modulate solar heat continuously. These technologies can provide significant benefits for most countries, particularly for hot and sunny climates, where dynamic solar control can offer dramatic cooling load reductions beyond those provided by low-e glazing. Dynamic solar control can also offer increased passive heating contributions when designed and operated correctly in colder climates.

In most mature economies, double-glazed windows with low-e glass are standard building products with large market shares. Many mature economies are now also pursuing triple-glazed windows (with two surfaces of low-e glass). However, much effort is needed to bring these technologies to emerging markets, and those markets need to "leapfrog" the transition from single-glazed clear glass windows to at least double-glazed low-e windows (and eventually triple-glazed low-e windows in cold northern zones).

Globally, more effort is also needed to implement air sealing in buildings so that air leakage (i.e. infiltration and exfiltration) is reduced, particularly because it can reduce heating, cooling and ventilation energy consumption by as much as 30%. Large variations exist between building practices and building stocks across the globe, but air sealing should generally be considered a high priority for both new construction and existing buildings everywhere. Air leakage may not be a critical requirement for energy savings in moderate climates that do not require the use of heating and cooling systems, but globally, and especially in developing countries with huge potential for space cooling demand, it should be considered a high priority for any building installing a space conditioning system.

Urban areas are a natural place to develop both knowledge and demand for efficient building envelope technologies, since cities offer large supply for building products and are often the first places to adopt building technologies when they are introduced to the market. Investments for local and/or regional manufacturing of efficient building envelope products is needed to enable commodity-based material pricing through local product supply chains. National and urban policy makers, along with building code officials, should also place much greater effort on improving construction practices and technology choices in cities to create the right market conditions and critical demand to bring efficient building envelope technologies to cost-effective scales.

Challenges and opportunities for urban building renovation

Building renovation, especially in developed countries with cold climates, is a critical priority for meeting 2DS objectives in the global buildings sector. Modest energy savings are often pursued through improved energy management or via individual component replacements (e.g. window replacement or modest levels of added insulation). However, these actions without deep energy efficiency measures represent a missed opportunity to achieve major energy savings with long-term cost-effective investments. A more assertive effort is needed to pursue deep energy renovations to drastically reduce space heating and cooling demand across the world's existing building stock.

Despite an increasing recognition of the importance of these renovations, very little progress has been made in establishing policies for their implementation. Often, building energy efficiency measures are "available and market-ready" when new building construction policies require energy-efficient technologies. However, the renovation market is much more challenging, because of the high variability of existing building conditions, multiple approaches to efficiency improvements and other external barriers, such as historical preservation or building association restrictions. As a result, there currently exist high transactional costs for deep energy renovations in most markets, leading to payback periods as high as 30 years. Consequently, low-cost financing can be challenging to obtain, as financial institutions typically do not readily trust the parameters associated with existing building energy-savings measures.[19]

For cities to support large reductions in building energy consumption, public policy needs to support deep energy renovations through a long-term perspective. In most markets, 10 to 15 years are necessary for deep energy renovation measures to become fully viable at competitive prices. Very-high-performance building technologies can be supported through a variety of incentives to help establish a market for better and more cost-effective products, typically within a decade of the initial market support. These market conditioning tools can then be used to transition technologies from voluntary to mandatory energy efficiency measures across existing building stocks when they undergo refurbishments or other major changes (IEA, 2013b). However, financial incentives for broad, sweeping energy renovations are needed first to enable system-level approaches to deep building energy renovations.

Some promising work has been done on scaling up deep energy renovations, on both the national and urban scales, to move this important agenda ahead (Box 4.5). Packaging of energy efficiency measures is another promising way to increase awareness and adoption of deep renovation measures in buildings. By packaging together short-term measures (e.g. with payback periods of two to ten years) with measures that have longer payback periods (e.g. major renovation), policy makers and building stakeholders can improve overall payback periods and encourage greater uptake of deep energy efficiency gains during planned building renovations.

One particular area that cities can support to enable deep energy renovations in urban buildings is through whole-building energy performance evaluation and disclosure. Many cities are already pursuing voluntary and even mandatory energy performance disclosure policies that function as a macro-level metric of building energy performance. The results of these disclosures can be used both to target poorly performing buildings in cities and to encourage additional private financing for energy efficiency measures by demonstrating the impact and return on deep energy renovation investments.

19 See focus of the Investor Confidence Project to improve financing for building renovation, www.eeperformance.org.

Box 4.5 Energiesprong and adaptation for urban buildings in the city of London

Energiesprong (Dutch for "energy leap") is an innovative building refurbishment programme that was created in the Netherlands with support from the Dutch government in 2010. It convened various building stakeholders (e.g. housing associations, builders and financiers) to organise a large-scale refurbishment proposition (initially 111 000 homes in Holland). The programme achieves deep energy renovations (in this case, net-zero energy performance* for building heating, hot water, lighting and appliances) within ten days using off-site pre-fabrication and with a 30-year energy performance warranty from the builder (Energiesprong, 2014).

By working with building stakeholders and bundling deep energy renovations across a critical building stock, Energiesprong has enabled a financial and regulatory environment that lowers investment risks for financers and eliminates up-front investment costs for consumers, who see no increase in their monthly energy bills (which are instead paid to an energy service provider rather than to a traditional energy utility). It has also created sufficient economies of scale to attract the participation of stakeholders (e.g. builders) that may not be interested otherwise in developing these packages if only for a small number of buildings.

Currently, the Greater London Authority is undertaking a detailed assessment of Energiesprong to establish the extent to which the programme could be transferrable to the metropolitan area of London. The assessment will consider the four key pillars of Energiesprong (notably, energy performance guarantees, delivery timescales, affordability and attractiveness) within the urban framework to establish the financial envelope for delivering net-zero energy renovations in London, including any planning, financial and regulatory issues, constraints or opportunities. The assessment will also look at how Energiesprong (currently working with public housing) can be delivered across other tenures (including notably private rented and owner-occupied housing).

The Greater London Authority is also engaging with key organisations and supply chains in the United Kingdom to consider how Energiesprong could be delivered successfully in the capital. The initial assessment is expected by mid-2016. Additionally, the Greater London Authority is working with the Carbon Neutral Cities Alliance to do an initial high-level assessment of the transferability of Energiesprong within the urban environment to other international cities.

* Net-zero refers to building energy consumption that is not higher than the energy produced by that building.
Note: More information about the existing Dutch Energiesprong programme can be found at http://energiesprong.nl/.

Energy performance certificates can be derived in a variety of ways, including actual measured data and using a building characteristic evaluation or asset rating. The building evaluation method usually involves simplified software rating tools, and credentials required of the auditor vary by programme. For instance, the Residential Energy Services Network (RESNET) programme in the United States requires energy auditors to meet criteria that are more stringent than mandatory certificates elsewhere, such as the energy performance programme that is widely used in the European Union (EU). The intent of the RESNET programme is to ensure that all performance ratings are of a very high quality; a drawback, however, is that market entry and programme costs are high, while market uptake is slow. A balance between rigour and accessibility is, therefore, needed to encourage greater uptake of this useful tool. Urban areas can help to propagate energy performance certificates while also using them to improve understanding of local building energy performances and market segmentations.

Opportunities for nZEB and ZEB buildings in urban areas

Many types of zero-energy, near-zero energy and net-zero energy (or emissions) building programmes, goals and definitions have arisen. These concepts include buildings that use very low energy and that have either on-site renewable energy resources (e.g. PV or solar thermal collectors) or are connected to an external source of "clean" or "green" energy, most typically augmented using heat pumping technologies.[20] The fundamental objective of these programmes is to pursue the construction of buildings that need as little energy as possible to ensure a substantial reduction in a building's carbon footprint. However, the balance between investments in building energy efficiency (with diminishing marginal energy savings) relative to increasing construction or refurbishment costs is not widely understood, because many ZEBs and nZEBs (collectively referred to as "(n)ZEB") have been demonstration or showcase buildings (often in single-family homes in non-urban areas).

The concept of (n)ZEBs has grown considerably over the past 20 years, and the cost-effectiveness of new (n)ZEB construction is increasingly viable, although typically in single-family and low-rise buildings in non-urban or peri-urban areas. In many parts of the world with low-to-moderate energy prices, more effort is needed to make (n)ZEBs fully market-viable without policy intervention. This need is particularly true for urban (n)ZEB construction, where costs and opportunities for multifamily and large commercial buildings in dense urban environments are less evident than in non-urban settings. While urban building demonstrations of low-energy buildings and ZEBs (and even an energy-positive[21] large-scale public building demonstration in Austria [IEA, 2013a]) do exist, these projects tend to involve buildings with large disposable areas that are not common in most dense urban building sites. More work is needed to demonstrate the potential for (n)ZEBs in dense urban environments.

Solar resources in urban areas for meeting (n)ZEB energy objectives can also be hindered by lack of adequate roof area and by shading from adjacent buildings. While vertical surfaces are an option for meeting energy generation requirements, they also have reduced energy production potential as a result of limited space, poor angle orientation and the need to maintain adequate daylight into buildings. Integrated technology solutions can offer improved renewable energy supply, but even then, total potential solar thermal heat and electricity production in a dense urban environment may not fully satisfy energy demand for some building types (see Chapter 6). Even so, solar technologies can still help provide zero-carbon energy for part of urban building space heating, cooling and water heating loads.

In many urban areas, near-zero and net-zero energy (or emissions) communities may be a more realistic goal for achieving a low- or zero-emission buildings sector. When (n)ZEBs are not feasible, because of technical limits or cost constraints, integrated energy solutions (e.g. low-energy buildings paired with advanced district energy, heat pumps, renewables and other carbon-neutral power generation, including excess heat recovery) can be a viable option to meet urban energy and emissions objectives through cost-effective investments. Integrated energy systems can also allow for greater flexibility, including increased use of variable renewable sources and thermal storage, and can provide overall improved local energy system efficiency.

20 See *Building Energy Performance Metrics: Supporting Energy Efficiency Progress in Major Economies* (IEA-IPEEC, 2015) for more details regarding variations and needs for improved metrics for ZEBs and low-energy buildings.

21 Energy-positive buildings refer to buildings that have more on-site renewable energy supply than energy demand.

Integration of energy-efficient buildings and district energy

Globally, significant amounts of heat are lost each year in power generation and from industrial processes. Co-generation[22] in global electricity production decreased from 11% in 2000 to 9% in 2013, despite having a global average efficiency of 59% in 2013, compared with 37% for conventional thermal power generation. Greater deployment of co-generation technology with efficient district energy networks could help to improve the intensity of global electricity and heat production while also reducing energy consumption for direct heat production in buildings.

The analysis in this section provides an initial assessment of building energy efficiency measures and efficient district energy (heating and cooling) options for reducing the energy intensity of urban buildings. Typically, these types of integrated analyses are conducted on a local or even network level, but broader assessments such as those described here can provide a first order of useful assessment for policy makers.

Increasing the uptake of deep energy efficiency measures to reduce space heating and cooling demand in buildings is essential to meeting 2DS objectives, as is providing low-carbon heating and cooling solutions in urban areas. Local planning and policy design can play an important part in meeting those targets, especially through enforcement of mandatory construction and building renovation codes and through support for efficient, low-carbon heat and chilled water supply options, including advanced district energy networks, heat pumps and solar technologies.

Worldwide, district heating has only a small fraction of the total building heat market (roughly 11% of global space heating and water heating energy consumption in 2013), while in some countries and regions, district heat networks are quite extensive. For example, more than 6 000 district heating systems are in Europe, and nearly 140 million EU citizens live in a city with at least one district heat system (Euroheat & Power, 2015). In China, the district heat network in north urban China accounted for more than 178 000 kilometres (km) in 2013, covering more than 90% of floor area in that region. By contrast, large district cooling networks are uncommon in most regions.

Historically, programmes for district energy networks have been pursued independent of renovations and investments in energy efficiency in buildings. Integrated analysis of the technical, economic, policy and business cases of integrated building policy is needed (e.g. the choice to expand or upgrade district heat networks, promote more efficient stand-alone technologies or mandate deep energy renovations in buildings) to minimise investments in energy performance and carbon emissions abatement across the energy economy.

Currently, a few projects and research programmes, such as the EU Stratego project,[23] are looking at the role of different energy efficiency options to achieve cost-effective pathways to meeting thermal comfort in buildings while also meeting broader energy and emissions targets to 2050. The work in this area is aimed at supporting more effective design of energy policies targeting efficient, low-carbon buildings, including technology and policy options to reduce heating and cooling demand in the urban built environment. Further work in this area is needed, including greater assessment of the effects of policies, climatic variations and varying energy prices on achieving a low-carbon footprint across the buildings sector and energy economy.

22 Co-generation is also commonly referred to as combined heat and power (CHP).

23 The Stratego project assesses multilevel actions for enhancing heating and cooling plans across the EU and bridges the gaps among EU policy, national objectives, and actions taken at the regional and local levels. More information can be found at http://stratego-project.eu/.

The analysis presented in this section shows that an opportunity exists to provide low-carbon, clean district heat to urban areas when paired with effective building energy efficiency measures. For many existing building types in cold climates (with energy performance often in the 90 kWh/m^2 to 150 kWh/m^2 range, or higher), pursuing deep energy renovations below the 50 kWh/m^2 to 70 kWh/m^2 range is not necessarily cost-effective.[24] However, options to meet remaining heat demand through high-efficiency equipment (e.g. heat pumps) or clean district heat can make low-carbon buildings more feasible.[25] These building renovation measures can also complement improved district heat efficiencies (e.g. through lower distribution temperatures) and can be planned strategically with district heat network expansion to meet additional building demand without increasing supply capacity.

The key to effective building and district heat integration is that the entire effort be properly planned, co-ordinated and implemented over a long enough period to engage stakeholders and allow for capital investment planning. This effort includes integrating building standards and energy supply policies under an urban or community plan supplemented by energy mapping and long-term energy growth scenarios.

Modernising existing district energy networks

Globally, many old district heat networks have large piping losses with inefficient heat production systems. For older systems reaching lifetime maturity, alternative approaches (e.g. deep building energy renovations with efficient, distributed heat generation) may make more sense in terms of needed investments or energy and emissions reductions. Other systems offer an opportunity to plan strategic investments in line with a more efficient buildings sector to achieve efficient, high-performance heat generation with net energy and emissions reductions across buildings and heat and power generation. When planned strategically, those integrated energy efficiency measures can even lower life-cycle costs for both buildings and district heat networks.

Modern, advanced and integrated district energy systems (with use of renewable and excess heat sources) are possible, including fourth-generation low-temperature (e.g. 50-55°C, or lower if using booster heat pumps) district heating systems and modern tri-generation (i.e. electricity, heating and cooling) district energy systems. International collaboration through the IEA Energy Technology Network[26] is assessing the technical potential and economic viability of these advanced, low-carbon district energy networks across different conditions and technical solutions. Research also includes assessment of more practical issues with modernising district energy networks (e.g. network sizing and timing of infrastructure upgrades). Continued effort in this area, along with modernisation of existing district heating networks to improve generation efficiencies and reduce system losses, will play an important part in meeting 2DS objectives for low-carbon heat in buildings (Box 4.6).

Building and district heat strategies in Stockholm, Sweden

The city of Stockholm, Sweden, had an urban population of 897 700 inhabitants in 2013, with a total metropolitan population of nearly 2.2 million people. The Stockholm municipality has a relatively old building stock compared with the rest of Sweden, and one of the highest population densities in the country, with roughly 4 800 persons per square

24 For new buildings, and even many existing single-family or low-rise buildings, even lower (e.g. nZEB or ZEB) performance levels are technically achievable and cost-effective.

25 Additional building envelope performance measures may be cost-effective when considered relative to emissions abatement costs across other sectors of the energy economy (e.g. transport and industry). Further assessment is needed in this area to improve global understanding of cost-effective emissions reduction opportunities.

26 More information on the IEA Energy Technology Initiatives can be found at www.iea.org/techinitiatives/.

kilometre (SCB, 2015). Space heating is the single largest energy load in Swedish buildings (roughly 55% of total final demand), and Stockholm city has a typical heating period from 15 September to 15 May.

Box 4.6

Advanced district heating solutions for energy-efficient, low-carbon communities

The IEA hosts several international initiatives that address the development and deployment of cost-effective DHC and CHP technologies in support of an efficient, low-carbon energy sector. These initiatives include the IEA CHP/DHC Collaborative,* established in 2007 as an international co-operation framework among government agencies, industry and non-governmental organisations assessing DHC and CHP technologies and related market issues and policies. Other initiatives include the IEA Technology Collaboration Programmes (TCPs) on District Heating and Cooling including Combined Heat and Power (DHC/CHP TCP) and the Solar Heating and Cooling Programme (SHC TCP).**

The DHC/CHP TCP work programme currently has two research projects related to technical assessments of district heat for urban buildings. One project is seeking to transform district heating systems from high to low temperatures; the other project is looking at optimising urban form for district energy to reduce GHG emissions and energy consumption. A similar project, Annex TS1, is currently assessing holistic and innovative approaches to communal, low-temperature heat supply, using district heating to connect demand (buildings) and generation in support of a 100% renewable-energy-based community.

Several examples of advanced, low-temperature district heating systems already exist in innovative energy systems implemented in communities in several countries participating in the DHC/CHP TCP. The Drake Landing solar community in Alberta, Canada, provides space heating needs for 54 residential buildings using 90% solar thermal energy, short-term and season energy storage, low-temperature district heat, and energy-efficient homes. Similar projects exist in Germany, Denmark, Norway and the United Kingdom, where low-temperature district heat for both existing buildings and new low-energy buildings in cold climates is being used to achieve low-carbon and even zero-carbon communities using combinations of renewable energy (e.g. solar thermal and geothermal), heat pumps, and efficient heat generation (e.g. biofuel boilers and high-efficiency CHP).

To date, examples of advanced, low-temperature district heating solutions for low-carbon and zero-carbon integrated energy systems have typically been small-scale (in terms of connected buildings and network size) projects, although some large-scale projects do exist (e.g. a Danish solar district heating system with 70 000 m^2 of solar collectors and 200 000 cubic metres of seasonal storage [Ramboll, 2015]). Further policy support and financial incentives are needed to facilitate investments in modernisation and improvement of the world's existing inefficient district heat networks (IEA, 2014). Continued support is also necessary for research activities and demonstration projects that can be used to design sustainable business models that reward innovation and flexibility for low-carbon, efficient, integrated energy systems.

* More information on the IEA CHP/DHC Collaborative can be found at www.iea.org/chp.
** More information on the IEA DHC/CHP and SHC TCPs can be found at www.iea-dhc.org and www.iea-shc.org.

The district heat system in Stockholm is the largest district heating and cooling network in Sweden (roughly 1 330 km of network length). It is an older, complex system operated by six district heat companies across several major networks with some interconnections among operators. Nearly 80% of total existing buildings in Stockholm are connected to the district heat network, including roughly 85% of total residential buildings and nearly 95% of multifamily residential buildings.

The largest portion of the building stock in Stockholm (roughly 80%) is multifamily residential buildings with an average of four to five storeys. Nearly two-thirds of existing residential buildings in Stockholm were built before the 1960s, and multifamily residential buildings built before 1960 account for more than half of total residential floor area. The typical space heating intensity (final energy) of those multifamily, pre-1960s buildings is above 130 kWh/m^2, whereas buildings built after the 1960s tend to have energy intensities of 90 kWh/m^2 to 110 kWh/m^2. Single-family buildings in Stockholm, while a much smaller share of residential floor area (roughly 20%), typically have lower energy intensities of 70 kWh/m^2 to 110 kWh/m^2. This difference is largely the result of the increasing use of heat pumps for space heating, which account for roughly 50% of single-family households (SEA, 2013b).

Building envelope energy efficiency potential

Analysis was conducted on three building renovation packages for 18 residential building classes (based on age and construction type), for a total of 54 building renovation packages. The renovation packages include building envelope measures (e.g. insulation, window replacement and air sealing), heat recovery from ventilation, and upgrade of equipment (e.g. electrical motors in circulation pumps). The renovation packages were considered with respect to the Swedish "national strategy proposed for energy renovation of buildings" (SEA and SNBHBP, 2013), and real investment data from renovation programmes initiated by the Swedish Energy Agency were used as part of the cost analysis.

Based on the assessment, it was determined that building energy efficiency measures would be cost-effective down to the 50 kWh/m^2 to 70 kWh/m^2 range for space heating intensity in most residential building types. Those savings (roughly 50-60% over the existing average residential space heating intensity) would have considerable effect on the district heat network, because options for expanding district heating to new connections (in-fill) in Stockholm are small. The network could be expanded to surrounding areas with lower heat densities (e.g. suburbs with single-family homes), but the costs for these types of expansions are typically much higher than adding additional connections within the existing network (due to infrastructure costs and increased distribution losses from lower heat densities).

Integrated energy assessment and conclusions

Over the last two decades, Stockholm has increasingly phased out fossil fuel use for district heat production, and fossil fuels now account for less than 15% of district heat generation. Approximately 60% of district heat is produced using biomass and municipal solid waste, while another 25% is produced using heat pumps (Fortum, 2014).

Because building energy efficiency measures have an important influence on district heat investment strategies, the analysis looked at nine possible scenarios for residential building energy efficiency measures with respect to district heat pathways in Stockholm (Table 4.3). These scenarios – ranging from minimal investments in buildings and district heat to aggressive building renovation schemes (e.g. greater than 60% stock improvement) and carbon-neutral district heat investments[27] – considered the effects of building energy efficiency measures on district heat investments to 2050.

27 The scenarios considered in this analysis assumed a carbon tax in support of low-carbon investments in buildings and the district heat network. Further information on the assumptions and methodologies applied in the case study can be found in Annex E online; see www.iea.org/etp/etp2016/annexes.

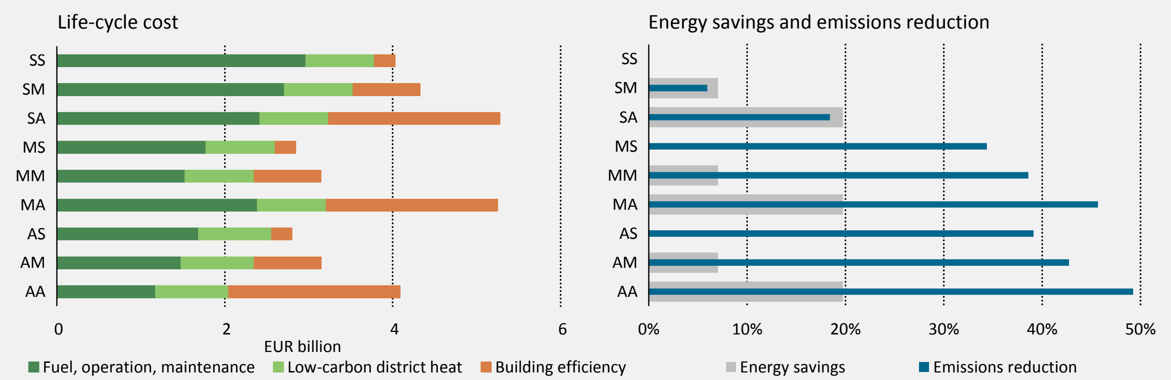
Table 4.3 Building energy efficiency and district heating investment scenarios for Stockholm

Building renovation rate / District heat investments	Standard 1% renovation, 15% stock efficiency improvement	Moderate 2% renovation, ~35% stock efficiency improvement	Advanced 3% renovation, 60% stock efficiency improvement
Standard Only planned network maintenance investments	SS (BAU)	SM	SA
Moderate Increased low-carbon investments	MS	MM	MA
Aggressive Strong investments for a carbon-neutral network	AS	AM	AA

Note: Scenario labels refer to the combination of district heating and building renovation investment choices, respectively (e.g. AM = aggressive district heat rates, moderate building renovation rates); BAU = business-as-usual; further information on the above scenarios can be found in Annex E online; see www.iea.org/etp/etp2016/annexes.

The nine scenarios for Stockholm were considered from a discounted life-cycle cost perspective (i.e. investments in district heat and energy efficiency measures in buildings, energy costs, and any operation and maintenance [O&M] costs) with respect to energy savings and CO_2 emissions reduction potential. The conclusions indicate that building energy efficiency measures without any intervention in the district heat network would result in the highest total life-cycle costs from a systems perspective, because capital and operational costs in the district heat network would offset savings from building energy demand reductions (Figure 4.10). Conversely, investments in low-carbon or carbon-neutral investments in the district heat network (e.g. additional excess heat recovery and solar thermal integration with seasonal storage, possibly in combination with heat pumps) would result in significant emissions savings at the lowest life-cycle costs. Energy and emissions reductions are naturally greater when moderate building energy efficiency measures are paired with district heat investments.

Figure 4.10 Costs and energy and emissions savings to 2050 for integrated buildings in Stockholm



Note: See Table 4.3 for scenario descriptions.

Key point *Moderate building efficiency measures in Stockholm, paired with carbon-neutral district heat investments, would lead to the greatest, most cost-effective energy and emissions savings in 2050.*

Moderate building renovations with an aggressive district heating pathway would lead to the most cost-effective energy savings and emissions reduction relative to a SS (or BAU) scenario. In this combination (scenario MA), the average residential building energy intensity is lowered to 85 kWh/m^2, and energy consumption and CO_2 emissions (buildings and district heat) are lowered by 7% and 43%, respectively. More aggressive building measures with carbon-neutral district heat would lead to greater energy and emissions reductions, but life-cycle costs would be higher because district heat capacity investments would not be fully utilised.

Further analysis of the influence of energy price variations (including carbon taxes and the availability and cost of excess heat recovery for district heat production) is needed to improve understanding of the cost-effective targets for building and district heat investments to 2050. Continued assessment of building technology cost curves would improve understanding of how deeply residential buildings could be renovated relative to district heat investments as building energy efficiency measures become more common (and therefore possibly less expensive). Additional research on the impact of lower heat densities on network distribution losses would also help to improve understanding of necessary district heat investments to 2050.

Energy conservation and low-carbon district heat in Turin

Turin (Italy) is a city of roughly 910 000 inhabitants in north-western Italy, with a total urban metropolitan population of roughly 1.7 million people. The region has a temperate, continental climate with moderately cold, dry winters (i.e. between -2°C and 5°C in January) that contrast with the Mediterranean climate along the coast of Italy. The heating period in Turin typically lasts from 15 October to 15 April.

More than 80% of residential buildings in Turin were constructed prior to the 1980s, before regulations were enacted on building energy consumption. Nearly half of the residential stock consists of multi-residential apartment block housing (i.e. greater than four storeys), which account for more than 80% of total residential building volume. Low-rise, multi-residential buildings account for another 19% of the housing stock (11% of volume), and another 21% of residential buildings are single-family attached housing (5% of volume). The remainder is single-family detached housing.

The city of Turin (excluding the surrounding metropolitan area) has roughly 36 500 residential buildings, accounting for roughly 47% of buildings in Turin, which cover approximately 50 million m^2 of floor area (150 million cubic metres [mcm] of volume), with an average space heating energy intensity of 170 kWh/m^2. Turin has the largest district heating network in Italy, serving roughly 570 000 inhabitants (or nearly 60 mcm of building volume) (IREN, 2014). Residential buildings that are connected to the district heat network (roughly 35% of residential building volume) have a lower heating energy intensity of about 110 kWh/m^2, which is largely because most residential buildings connected to the network are multifamily buildings.

Single-family households have some of the highest space heating energy intensities (see Figure 4.3), although these buildings only account for less than 10% of total residential space heating energy consumption. Deep energy renovations in Turin's multifamily residential buildings (with the largest share of residential floor area and space heating energy demand) are, therefore, essential to reduce space heating energy demand. More efficient multifamily residential buildings will also help to reduce the impact of residential heat curve loads on Turin's district heat network.

Building envelope energy efficiency potential

Energy conservation through more efficient building envelopes will be essential to meeting objectives to lower space heating energy consumption across Turin's building stock. Analysis was conducted on four building renovation packages for 36 residential building classes (Corgnati et al., 2013; Mutani and Vicentini, 2015; Delmastro et al., 2015).

The renovation packages (which consider a combination of building envelope and equipment measures) were simulated for each of the 36 reference building classes in Turin. An additional 25 renovation packages were simulated for both multifamily, high-rise buildings built before the 1970s (the largest portion of the residential building stock) and single-family, detached houses built before the 1980s (the most energy-intense portion of the residential building stock) (TABULA, 2012; Guala, 2013; Fausone, 2013). These renovation packages were then assessed for energy reduction potential relative to total life-cycle costs.

The analysis concluded that the cost-optimal range for building energy efficiency measures across the various Turin residential building stock types was typically 45 kWh/m^2 to 75 kWh/m^2. Energy efficiency measures beyond those levels of renovation, while technically feasible, generally came at higher costs with much lower or no return on investment.

Integrated energy assessment and conclusions

District heat is currently produced using gas-based co-generation and gas boilers, along with a small (12 500 cubic metres) daily storage system. Roughly 35% of residential building volume in Turin is connected to the heat network, and 93% of the connections are in the residential sector. Energy-saving measures in Turin's residential stock would, therefore, have an impact on district heat production, costs and investment strategies.

The analysis considered nine possible scenarios for residential buildings and district heat in Turin to explore the effects of building energy efficiency measures on district heat and to improve understanding of potential cost-effective pathways for building energy conservation relative to district heat supply options (Table 4.4).

Table 4.4 Building energy efficiency and district heating investment scenarios for Turin

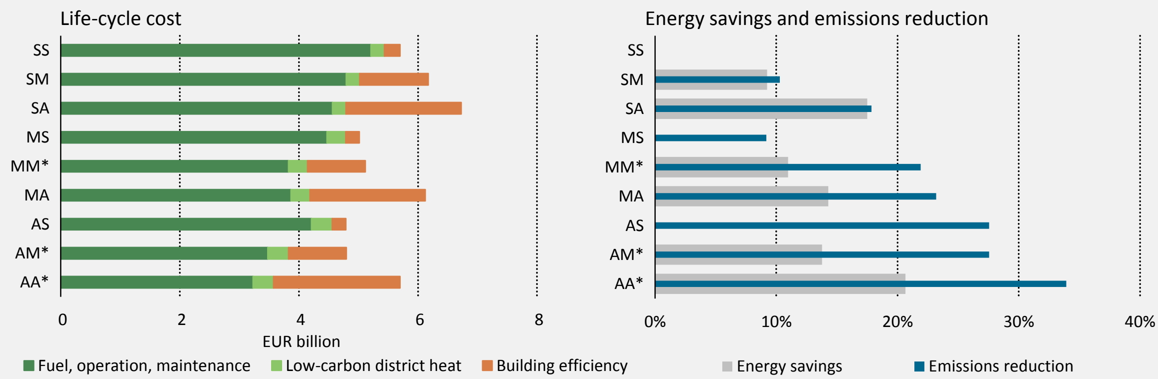
Building renovation rate / District heat investments	Standard 1% renovation, <10% stock efficiency improvement	Moderate 2% renovation, 30% stock efficiency improvement	Advanced 3% renovation, 55% stock efficiency improvement
Standard Little expansion, few investments	SS (BAU)	SM	SA
Moderate Slight expansion, low-carbon investments	MS	MM*	MA
Aggressive Moderate expansion, carbon-neutral investments	AS	AM*	AM*

*Indicates further expansion of the district heat network at or below previous heat output capacity because of building envelope energy efficiency renovation packages.
Note: See Table 4.3 for scenario descriptions; further information on the scenarios can be found in Annex E online; see www.iea.org/etp/etp2016/annexes.

The nine scenarios – ranging from minimal investments in buildings and district heat to aggressive building renovation schemes (e.g. greater than 50% stock energy performance improvement) and carbon-neutral district heat investments – were considered from a discounted life-cycle cost perspective (i.e. investments in district heat and energy efficiency measures in buildings, energy costs and any O&M costs) with respect to energy savings and CO_2 emissions reduction potential. Opportunities (and costs) for district heat expansion relative to building energy efficiency measures were also considered in some of the scenarios, and a carbon tax was assumed in support of low-carbon investments in buildings and the district heat network.[28]

The conclusions of the scenario analyses found that energy-saving measures in buildings without any intervention in the district heat network would not reduce the life-cycle costs from a systems perspective because of capital and production costs with continued gas-based district heat production (Figure 4.11). Investments in low-carbon or carbon-neutral investments in the district heat network (e.g. excess heat recovery and solar thermal integration with seasonal storage) would allow for important emissions savings, although energy and emissions reductions are naturally greater with more aggressive building energy efficiency measures. The combination of moderate to advanced building renovations with an aggressive district heating pathway would lead to the greatest savings relative to a SS (or BAU) scenario.

Figure 4.11 **Costs and energy and emissions savings to 2050 for integrated buildings in Turin**



*Indicates further expansion of the district heat network at or below previous heat output capacity because of building envelope energy efficiency renovation packages.
Note: See Table 4.4 for scenario descriptions.

Key point *Moderate-to-advanced building stock renovations with an aggressive, carbon-neutral district heat pathway would allow for the greatest energy and emissions savings below BAU life-cycle costs.*

In these scenarios, the energy savings from the building heat demand would allow for increased use of smaller-scale heat production plants and greater use of low-grade heat from renewable sources or excess heat. The reduced building energy demand would also allow for expansion of the district heat network at or below previous heat output capacity, thereby lowering the cost of district heat production and further reducing energy consumptions and CO_2 emissions from buildings that were not previously connected to the network in Turin.

28 Further information on the assumptions and methodologies applied can be found in Annex E online; see www.iea.org/etp/etp2016/annexes.

A strategic long-term vision will be necessary for Turin's building stock and district heat network to encourage the effective planning and implementation of building renovation measures and district heat network investments. This is especially true for Turin's district heat network, because predictability of heat demand and load curves is critical to district heat capacity and operation investments. Future analysis should consider the influence of energy price variations on decision-making structures. Consideration of various discount rates, financial incentives and market conditions relative to investment decisions and energy and emissions reductions would similarly improve the understanding of the range of suitable options and interventions in Turin's buildings and district heat network.

Integrated solutions for energy-efficient buildings and district heat in Qianxi

The district heat network in China covers 90% of floor area in north urban China, or roughly 11 billion m^2, making it the largest and fastest-growing district heat network in the world (Euroheat & Power, 2015). Heating in northern China is a major portion of total Chinese building energy consumption, accounting for roughly 5.3 EJ in 2013 (or roughly one-quarter of total primary energy consumption by buildings in China). The average space heating intensity of buildings connected to the district heat network in northern China was around 130 kWh/m^2 in 2013. While energy consumption per unit of floor area has decreased over the past decade as new efficient buildings are constructed, the substantial growth in total floor area continues to drive increases in heat demand in absolute terms (IEA-TU, 2015).

District heat in north urban China is predominantly fuelled by coal, which accounts for more than 80% of commercial heat production in China. Coal-fired boilers accounted for 48% of primary energy used for commercial heat production in 2013, and co-generation (mostly coal) accounted for 42%. Gas-fired boilers accounted for another 8%, with the remaining 2% coming from various sources (e.g. small-scale co-generation and heat pumps) (TU, 2014). Without assertive effort to improve the intensity of building heat demand and also to improve the energy efficiency of heat generation, total primary energy consumption for heating in northern China could reach as much as 7.3 EJ by 2030, when total heated floor area is expected to reach 15 billion m^2 (TU, 2015). This growth would place heavy pressure on energy supply chains and the environment.

To reduce the intensity of heat demand in buildings, energy-efficient buildings have been promoted heavily over the last two decades, including policies and programmes to renovate existing building stock in northern China through insulation and envelope improvements (IEA-TU, 2015). Typical annual heat demand in many buildings in north urban China consequently ranges from 60 kWh/m^2 to 100 kWh/m^2, and further work on renovating existing building stock was announced under the 2013 *Green Building Action Plan* (MOHURD, 2014).

The Chinese government has also identified the critical need to improve the efficiency of district heat supply (e.g. through high-efficiency co-generation and excess heat utilisation). Low-grade heat recovery is a particularly promising area for energy efficiency gains, because power generation and industrial plants in China release large amounts of heat into the atmosphere each year. Low-grade excess heat released during the winter heating period is estimated at approximately 2.6 EJ per year, which, if recovered, could replace most of the existing coal-fired boilers in the district heat network and satisfy new demand in the future (Fang et al., 2013).

Energy-efficient buildings and integrated district heat demonstration in Qianxi

Qianxi county is an administrative district of roughly 390 000 persons in the eastern part of Tangshan city (China). District heat, using coal-fired boilers, has historically been the main source for space heating in the downtown area of Qianxi. The winter heating period lasts from roughly 15 November to 15 March each year, with an average temperature of -7.8°C in January.

Heated floor area in Qianxi is currently around 3.2 million m^2, with a current peak heating load of around 45 watts per square meter (W/m^2). Around 40% of the heated floor area consists of old buildings with poor insulation and air infiltration and a larger shape factor. These buildings have a measured peak heating load that is typically higher than 50 W/m^2. The remaining stock is newer buildings that were constructed under China's energy-saving standards that have progressively required lower energy intensities in new buildings since 1980. These buildings have peak heating loads that are less than 50 W/m^2, with newly built construction in recent years having peak heating loads under 30 W/m^2. Altogether, the average peak heating load in Qianxi is around 45 W/m^2, with annual heat consumption around 93 kWh/m^2.

By 2020, total heated floor area is expected to reach nearly 6.9 million m^2, and as high as 10.8 million m^2 by 2030. If assertive efficiency measures are not taken to address building heating intensities, peak district heat demand could therefore increase from 145 megawatts (MW) today to as much as 310 MW in 2020 and nearly 490 MW in 2030, with annual heat consumption rising from roughly 400 GWh today to as much as 1 000 GWh in 2030. Even if all new building construction meets the expected new standard for energy consumption in buildings, peak district heat demand could still increase to as much as 256 MW in 2020 and 373 MW in 2030 (or roughly 530 GWh in annual heat consumption in 2020 and 770 GWh in 2030).

The rapid growth of building floor area and expected growth in district heat demand pose a central challenge to meeting energy and environment objectives in Qianxi, including restrictions on future coal combustion. A demonstration project was, therefore, developed in 2014 to recover excess heat from two nearby steel plants (J and W), with the aim of recovering low-temperature excess heat from local industrial processes for the district heat network.[29] With this heat recovery, the peak heating potential was estimated at 217.5 MW, which could serve the basic district heat load[30] to 2030 and provide up to 650 GWh during the winter heating period.

Most of the first stage of the demonstration project at plant W was completed in January 2015. Pipelines were constructed to connect the heat recovery sources in the two steel plants and the existing district heating network in downtown Qianxi. A new heating station was also established beside the W steel plant, and heat exchangers were installed to recover excess heat from flushing water and mixed steam at the W plant. In the second and third stages, absorption heat pumps and absorption heat transformers will be installed at the J steel plant and then within the district heat network substations to lower return water temperatures and improve system efficiencies.

The Qianxi project was developed as part of a public-private partnership between the local government, which owns a 5% stake in the project and which serves as an intermediary between the local industries and citizens, and the J and W steel plants.

29 While use of industrial excess waste heat can be an efficient, cost-effective heat source for district energy networks, it should be first considered internally within the industrial processes.

30 The basic heat load is the lowest heat load during the winter heating period. It usually amounts to around 60% of the peak heat load.

The district heating company services the district heat network with the franchise right rented from the local government. The excess heat recovered from the steel mills is purchased at 4.5 Chinese Yuan renminbi (CNY) per gigajoule (GJ). Local buildings then pay a heat price of CNY 23/m^2.

The total investment for the first phase of the demonstration project was approximately CNY 283 million (Table 4.5). The second phase is expected to cost an additional CNY 51 million, and the third phase an additional CNY 110 million. The expected annual district heat production cost reduction is nearly CNY 30 million in 2016, leading to an annual cost reduction of CNY 63 million in 2030. The completed projected is therefore expected to have a payback period (static) of roughly seven years across the entire three phases.

Table 4.5 Cumulative integrated network investments, annual cost reduction and static payback period

CNY million	2016	2020	2030
Long-distance transportation pipeline	170	170	170
Devices and pipelines in plants	113	113	128
Heat station	*20*	*20*	*20*
Pipes inside the steel plant	*45*	*45*	*55*
Heat exchangers	*30*	*30*	*35*
Absorption heat pumps	*18*	*18*	*18*
Advanced heating substations	-	46	146
Total cumulative investments	**283**	**334**	**444**
Annual cost reduction	28	41	63
Static payback period (years)	**10.1**	**8.1**	**7.0**

Note: Investments in equipment retrofits in substations are estimated at CNY 0.3/W (heating power), mainly for the installation of absorption heat transformers.
Source: Yermao, L. et al. (2016), "Case study on industrial surplus heat of steel plants for district heating in Northern China," http://dx.doi.org/10.1016/j.energy.2016.02.105.

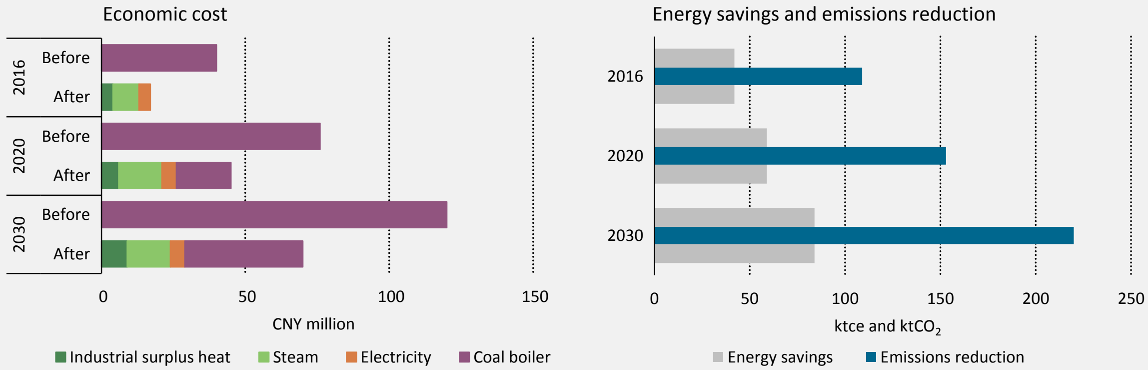
Performance of the integrated system and future potential in north urban China

The actual heat recovery efficiency of heat exchangers has been calculated since the installation at plant W in January 2015. The blast furnace slag is able to provide 105.5 MW of heat, including 90.5 MW for the district heat network and 15 MW for factory heating. Another 44 MW from steam could be captured. When the absorption heat pumps at the network substations are installed, the integrated system is expected to provide a peak of 165 MW (or approximately 340 GWh for the 2015/16 heating period). In future stages of the project, when capacity at plant J is added and additional absorption heat transformers are installed in the network substations, the heating power could reach 225 MW (or roughly 480 GWh of potential heat for the winter season in 2020 and 650 GWh in 2030).

Compared with the traditional coal boiler system, the integrated district heat and industrial excess heat recovery system reduces coal consumption by nearly 1.2 petajoules (PJ), leading to a potential energy savings through excess heat recovery of nearly 2.5 PJ in 2030. Local pollutant improvements from replacement of the traditional coal boilers include a reduction of nearly 355 tonnes (t) of sulphur dioxide (SO_2) and 310 t of nitrogen oxides (NO_x) in 2016, leading to an estimated reduction of 715 t of SO_2 and 620 t of NO_x in 2030.

The new integrated system does use more electricity,[31] but the net effect is still a large reduction in energy consumption and emissions, with positive return on the investments in an acceptable period of less than ten years (Figure 4.12). Since most of the delivery pipes and recovery equipment were invested in the first stage, the economic benefit from energy savings will improve over time as more excess heat is recovered and the system efficiencies improve.

Figure 4.12 **Heat generation costs and energy and emissions savings from excess heat recovery in Qianxi**



Note: tce = tonnes of coal equivalent; industrial surplus heat purchases cost roughly CNY 4.5/GJ, steam purchases CNY 32.5/GJ, electricity purchases CNY 0.65/kWh, and coal purchases CNY 28/GJ. The thermal efficiency of a coal-fired boiler is roughly 85%.
Source: Yermao, L. et al. (2016), "Case study on industrial surplus heat of steel plants for district heating in Northern China," http://dx.doi.org/10.1016/j.energy.2016.02.105.

Key point *The Qianxi integrated district heat project demonstrates the energy, emissions and economic benefits of excess heat recovery potential in China for meeting buildings sector heat demand.*

The Qianxi project demonstrates the capacity for industrial excess heat recovery[32] in district heating networks using cost-effective measures with reasonable payback periods (i.e. less than ten years) and considerable energy and emissions savings. Both steel companies and the district heat network achieved improved profits because of the synergies provided by excess heat recovery, and the social benefits (e.g. reductions in local pollutants and stable district heat costs) are considerable. When paired with building energy efficiency measures, the net benefits, including energy and emissions savings, could be even greater.

China announced plans in late 2015 to assess industrial excess heat recovery potential for district heat in 150 cities (NDRC, 2015). If urban areas with access to excess heat sources were to apply integrated solutions similar to the Qianxi project, district heat energy consumption and consequent emissions could be significantly reduced in north urban China, while also reducing economic costs and carrying multiple environmental and health benefits. Further action on building energy efficiency measures will also play a key role in reducing the energy intensity of space heating in north urban China. Energy efficiency improvements in buildings will also allow for increased access to district heat without necessarily expanding district heat capacity.

31 The heat from mixed steam has traditionally been used to generate electricity in the steel mills, with a thermal efficiency of around 18%. Under the new integrated system, the steam is recovered for district heat, and electricity is therefore purchased from the grid to compensate the difference.

32 See Chapter 6 for more information on excess heat recovery potential in China.

Investment synergies for low-carbon district energy

The integration of modern district energy networks and renovated, energy-efficient buildings will require greater co-ordination and financial support to align appropriate clean energy, low-carbon solutions. The overwhelming majority of district energy networks today continue to have a business operation and investment approach that is driven by core economics (i.e. heat sales). Under this business model and market structure, building energy efficiency improvements are not necessarily advantageous to district energy network operators, because it means lower sales. However, integrated, advanced district energy can provide low- or zero-carbon heating and cooling for buildings in urban environments in support of 2DS objectives, while still ensuring that district energy providers can operate on an economically viable basis and cover network investments. This balance is especially true in most urban areas with existing district energy networks, where as much as 30 to 40 years will be needed to fully renovate the existing building stock, even with extremely aggressive public policy to pursue deep energy renovation.

The challenge to transform DHC networks over time and to achieve a more efficient building stock is not insurmountable, but will require engagement of all stakeholders, including district energy providers and consumers. If given the right incentives and market conditions, district energy networks can be the drivers of this process by taking a longer-term, proactive position, where they help serve as energy service providers or as system integrators. Long-term stability of policy strategy that incentivises energy efficiency, flexibility and innovation, and that enables fair market conditions to reward those choices, is needed to encourage uptake of integrated building energy efficiency and clean district energy (IEA, 2014). This strategy includes policy and financial measures to reduce the risks of up-front investments.[33]

Recommended actions for the near term

Action is needed now to put the buildings sector on the right pathway to achieving energy efficiency and sustainability objectives. Key policy actions in the buildings sector can deliver significant energy savings and emissions reduction by stimulating widespread deployment of energy-efficient technologies, including efficient building envelopes and advanced and renewable heating and cooling systems.

Improving adoption and enforcement of mandatory policies for low-energy new building construction is a necessary first step for all countries, and improved capacity building (including education and training) is needed in many countries to ensure that building energy code compliance is standard practice. Deep building renovation measures for the existing building stock are also needed in many regions, particularly OECD countries, where the bulk of buildings in 2050 are already constructed today. To achieve 2DS objectives in the buildings sector before or in 2050, a global “race to the moon” approach is needed to bring deep energy renovation and (n)ZEBs from small-scale demonstration to mass-market penetration.

With national support, city governments can lead on the critical tasks of adopting, monitoring and enforcing building energy codes for new construction and a global uptake of deep energy renovation in existing buildings. These efforts could include deep energy renovations in public and municipal buildings, creating incentives and local energy efficiency programmes that support deep energy renovations in the private sector, and supporting development of efficient and low-carbon energy communities through integrated energy technology solutions. Energy efficiency measures in buildings can also deliver numerous multiple

33 Further information on how policy and market regulations can help mitigate market failures in support of efficient, low-carbon heat supply can be found in the IEA report *Linking Heat and Electricity Systems: Co-Generation and District Heating and Cooling Solutions for a Clean Energy Future* (IEA, 2014).

benefits for local communities, including job creation, improved air quality, more affordable energy, reduced maintenance costs and improved access to stable, efficient energy networks.

Through regulatory, planning and zoning functions, urban authorities can work with local stakeholders to establish the right market conditions and policy frameworks to achieve building energy efficiency potential. Action in this area is critical over the coming decade to ensure that the process is widely available and becomes standard practice. National programmes and initiatives (e.g. quality management and certification systems) can help to ensure a "common language" for all stakeholders, which will help to improve uptake and awareness of energy-efficient technologies and practices.

National policies have a substantial influence in enabling effective, sustainable urban energy planning through regulation (e.g. enforcement of codes and standards), fiscal policies (e.g. tax incentives, housing loans and third-party financing), national land-use planning frameworks, and capacity-building programmes. Greater support of local energy efficiency action is needed from national governments to encourage widespread deployment of cost-effective energy efficiency measures in the buildings sector. This support includes building the right policy and market conditions, promoting advanced building components through appropriate pilot and demonstration programmes, and in the short to medium term, providing financial incentives aligned with long-term objectives to help establish market demand (while avoiding use of short-term financing that does not align with broader objectives). This support also includes market conditioning that is needed to meet specific urban needs through the integration of energy-efficient buildings and flexible district energy networks.

Globally, increased efforts are needed to achieve high market penetrations of energy-efficient building technologies, including high-efficiency windows, insulation, appliances, lighting and other building services equipment (e.g. space heating and cooling equipment) through MEPS and product regulations. While most building technologies and policies are not exclusive to urban areas, cities can nevertheless play an important role in supporting the infrastructure for developing energy-efficient services and products locally. Local initiatives through awareness programmes, incentives, energy performance rating and reporting programmes, and engagement with local building stakeholders can help ensure that efficient products are available and used as standard practice. Sharing best practices and innovative local solutions, for example through the C40 building efficiency networks, can also help to increase development and adoption of low-carbon, energy-efficient technologies and practices in the urban buildings sector.

The integration of energy-efficient buildings and modern district energy networks using heat pumps, renewable energy technologies, thermal storage and other low-carbon heat sources (e.g. excess heat recovery) in dense urban areas can put the buildings sector and local energy networks on a sustainable, efficient 2DS pathway. These integrated networks are an important opportunity, especially in temperate and colder climate cities where improved cost-effectiveness across multiple, integrated solutions can move projects from being technically feasible to market achievable. This will require increased financial support and policy co-ordination to create long-term stable markets that incentivise energy flexibility and energy efficiency.

Further research of district energy network modernisation and the effects of deep efficiency improvements in buildings is needed. This research should include greater assessment of the effects of energy efficiency policies, climatic variations and varying energy prices on achieving a lower carbon footprint across the buildings sector and broader energy economy. Additional assessments will also be needed of the market and regulatory barriers on both the local and national levels that either encourage or hinder the pursuit of more optimised, integrated sustainable local energy systems.

Lastly, data, and a more acute sense of building energy needs and opportunities, are valuable tools that both national and local governments can use to analyse and shape policy decisions and prioritise energy efficiency efforts. Data can also play a critical role in targeting the right stakeholders on both the local and national scales to increase adoption of energy efficiency. Greater effort to improve global understanding of buildings sector energy performance and efficiency therefore should be a priority across all countries to select the right measures to put the buildings sector on an efficient, sustainable and cost-effective 2DS pathway.

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Chapter 5

Sustainable Urban Transport

Urbanisation, population growth and rising incomes are increasing the demand for urban[1] mobility. Meeting this growing demand while minimising environmental and public health impacts will require reducing greenhouse gas (GHG) emissions, local air pollutants and congestion, and improving energy efficiency and diversification. To realise this transition to sustainable urban transport, local and national policy makers need to implement a broad portfolio of measures.

Key findings

- ***Enhancing the sustainability of transport systems, including limiting GHG emissions to a level compatible with a global average temperature increase of 2°C (the 2°C Scenario [2DS]), will require ambitious, systemic, long-term policy commitments by national and local administrations.*** *Private-sector stakeholders, reacting to policy signals, will deploy the technologies and mobilise the necessary investments.*

- ***Globally, around half of passenger transport activity takes place in urban environments, reflecting the even population split between urban and non-urban areas.*** *Urban transport accounts for an estimated 40% of transport energy use[2] (107 exajoules [EJ]) and "well-to-wheel" (WTW) GHG emissions (9.1 gigatonnes of carbon dioxide equivalent [GtCO$_2$-eq]).[3]*

- ***Urban passenger travel generally relies more on personal cars in member countries of the Organisation for Economic Co-operation and Development (OECD) than in non-OECD economies.*** *This trend is apparent despite considerable variation across cities, countries and regions.*

- ***Rising personal incomes are expected to increase dependence on car travel.*** *Personal vehicles will continue to account for most future growth in personal mobility in urban areas, particularly where few policies limit the social and environmental impacts of personal vehicles. Cars' share of transport grows fastest in non-OECD economies.*

- ***In the 2DS, policies maintain cars' current share of urban passenger transport at 46%, well below the range by mid-century in other scenarios (56% to 62%).*** *In OECD member countries, this translates to a net decline in passenger travel by personal vehicles starting in the 2020s. Urban passenger car activity in non-OECD economies increases in all scenarios. Without strong policies to limit car ownership, the global car stock may grow from about 1 billion cars to 2.75 to 3.0 billion by 2050, against 2.3 billion in the 2DS.*

1 The definition of urban areas matches the United Nations' 2014 estimates of urban populations (UN DESA, 2014).
2 Unless otherwise noted, all references to energy use are expressed in terms of final energy.
3 Long-distance, intercity transport with high emissions intensity (such as aviation or road freight) or with considerable aggregate activity (such as shipping) explains the lower shares of urban energy demand and GHG emissions.

- ***Motorised 2- and 3-wheelers provide an increasing share of urban passenger activity, especially in rapidly developing Asian countries.*** *The degree to which they might serve as a viable substitute for cars has significant ramifications not only for local issues such as air quality and congestion, but also for global fuel demand and car stock.*
- ***In the 2DS, global energy consumption in transport (urban and non-urban) decreases by 6% between 2015 and 2050.*** *Energy use in the 2DS in 2050 is 45% lower than in the most conservative scenario, in which transport energy use increases by 72% over 2015. In the 2DS, WTW GHG emissions reach 6.1 GtCO*$_2$ *in 2050, about two-thirds the 2015 level.*
- ***Globally, modifications to urban transport can deliver nearly half of the sector's cumulative energy savings and more than two-fifths of cumulative emissions reduction in the 2DS by 2050.***[4]
- ***In the 2DS, vehicle electrification translates the benefits of decarbonised power generation into transport.*** *Electric powertrains penetrate fastest in urban passenger and freight transport. Meeting 2DS goals requires that 2-wheelers become fully electrified by 2050. The global stock of electric cars and freight delivery vehicles will need to exceed 150 million by 2030 (9% of the total fleet) and approach 1 billion by 2050 (about 40%).*

Opportunities for policy action

- ***Enacting policies that meet 2DS goals is very challenging. It will require policy and technology deployment in all regions, targeting all modes of urban and non-urban transport.*** *Action from national authorities lays the foundation for further measures by local administrations. Policy tools at all administrative levels need to be grounded in an analysis of all costs and benefits to be credible, effective and sustainable. Transparent and reliable policy tools are needed to guide the private sector toward investments required to successfully deploy advanced technologies.*
- ***There are three main pathways to meeting the 2DS goals in the transport sector: 1) avoiding transport activity*** *through policies influencing urban structures and increasing the time and money cost of driving;* ***2) shifting mobility*** *toward less carbon-intensive modes; and* ***3) improving vehicle efficiency and reducing the carbon intensity of fuels*** *through fiscal and regulatory measures.*
- ***National authorities can implement the key policies essential to meeting 2DS targets: 1) introducing fuel taxation based on WTW GHG emissions*** *is the linchpin policy driving reductions in GHG emissions;* ***2) implementing vehicle purchase and circulation taxes*** *to reduce vehicle ownership and provide revenue that can be invested in alternative modes; and* ***3) expanding and strengthening fuel economy and pollutant emissions regulations****, including taxes based on vehicle efficiency; and* ***4) providing stable support for research, development and deployment (RD&D) of innovative technologies*** *that enhance the efficiency and diversify the energy supply of transport.*
- ***Local authorities need to implement a strong portfolio of policies that reduce congestion and local pollution from transport and increase safety.*** *Densification of sprawling urban areas and compact, public-transport oriented development of new urban areas should be priorities. Congestion charging, regulatory restrictions limiting the use of the most polluting vehicles, and incentivising advanced vehicle technologies, as well as investment in public transport, are best suited for urban areas with sufficient density.*

4 The lower urban GHG emissions reduction is explained by the progressively lower share of urban GHG emissions across the projection period: this counterbalances the effect of higher GHG reduction shares in urban environments.

This chapter recommends actions that need to be taken up to 2050 to make the transition to sustainable urban[5] transport according to three scenarios:

- the 6˚C Scenario (6DS), in which policy developments beyond current targets are limited and technology improvements are incremental
- the 4˚C Scenario (4DS), which takes into account recent transport policies and technology deployments aimed at limiting GHG emissions, as well as continuing policy efforts to improve energy efficiency and address other transport issues, including local pollution
- the 2DS, which is consistent with the goal of limiting the global average increase in temperature to 2°C; enhancing the sustainability of transport systems with respect to pollutant emissions, congestion and noise; and requiring parallel efforts in other areas of the energy system.

Stocks and activity of motorised passenger and freight transport modes were allocated based on geographic location as urban, non-urban or some combination of the two (Table 5.1). Although passenger 2- and 3-wheelers and freight 3-wheelers are not exclusively urban, few reliable data are available for disaggregating their stocks and activity globally, or even in economies (such as China) where they constitute sizable shares of transport. Moreover, as they are used most often at low speeds and short to medium distances, the urban designation is more accurate from the perspective of usage characteristics, even if it does not accurately depict geographical areas of activity.

Table 5.1 Characterisation of motorised transport modes by geography of ownership and operation

	Urban	Non-urban	Both
Passenger	Passenger 2- and 3-wheelers	Passenger aviation	Passenger light-duty vehicles (PLDVs, or cars) Bus (urban, intercity) Rail (metro and urban light rail, intercity)
Freight	Freight 3-wheelers	Heavy freight trucks (HFTs) Freight rail Marine shipping and navigation	Light commercial vehicles (LCVs) Medium freight trucks (MFTs)

Current status of urban and non-urban transport

Transport contributed 23% of global energy-related CO_2 emissions in 2015.[6] After power generation, it is the sector that has experienced the most growth in emissions since 1990, driven by increasing energy demand and marginal changes in the carbon intensity of the fuel portfolio.[7] Transport is also the least diversified energy demand sector: oil products represent more than 93% of final energy consumed.

5 The chapter discusses non-urban transport (e.g. intercity passenger travel, long-distance freight) only to provide context, contrast with or clarify urban drivers, trends and patterns. For a broad overview of recent trends and national, regional and global trajectories, see "The Global Outlook" (Chapter 1). For a more general overview of recent trends and key near-term policy actions needed to bring sectoral GHG emissions in line with the 2DS, see the transport section of Chapter 2, "Tracking Clean Energy Progress." Investment costs of vehicles and infrastructure under the 6DS and 2DS are discussed in Chapter 1, in the section on transport.

6 The year 2015 is taken as the base year of the analysis conducted here since the *IEA Mobility Model* runs on five-year time steps from 1975 to 2050 (www.iea.org/topics/transport/subtopics/mobilitymodelpartnership/). Readers should note that all values for 2015 are extrapolated based on historic data from time series that extend through 2013.

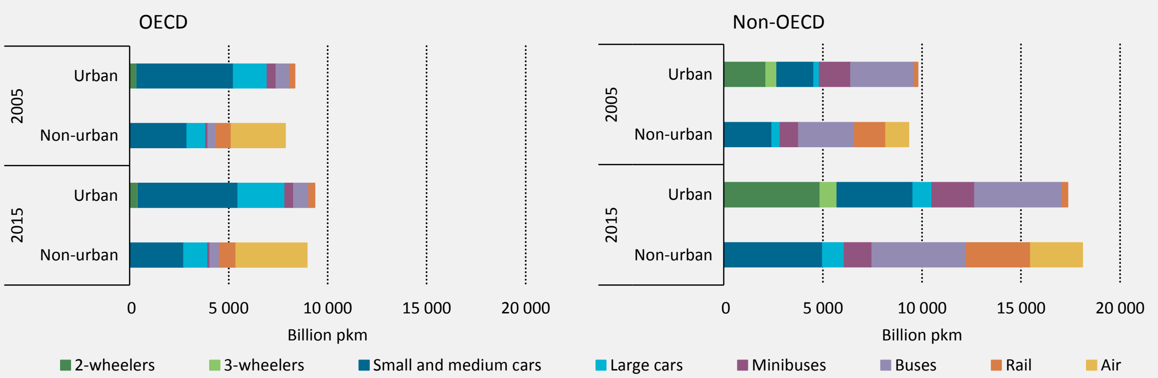
7 Since 2000, however, emissions have grown faster in the industrial sector, driven by booming cement and steel production, especially in China.

Transport energy demand and GHG emissions have grown as transport activity has increased. Energy and emissions have also grown as a result of changes in the relative importance of different transport modes, and despite reductions in the energy intensity of each mode and in the carbon content of fuels. These characteristics have developed differently in urban and non-urban contexts.

Passenger transport activity

The number of urban dwellers surpassed that of non-urban residents in the past decade (UN, 2014). Globally, about half of total passenger transport activity (measured in passenger kilometres [pkm]) now also takes place in urban environments (Figure 5.1).

Figure 5.1 Passenger transport activity, 2005 and 2015



Note: Figures and data that appear in this report can be downloaded from www.iea.org/etp2016.
Source: IEA (2016), *Mobility Model*, January 2016 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

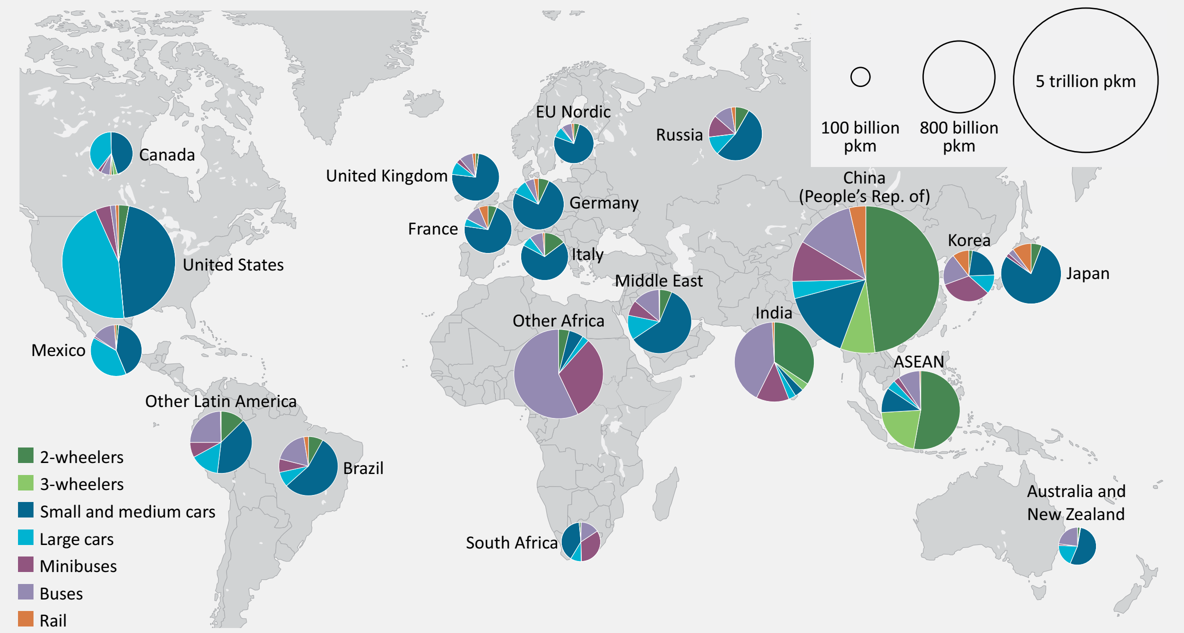
Key point *Passenger activity is roughly evenly split between urban and non-urban areas, but the mix of modes varies widely. In OECD member countries, urban mobility is primarily provided by cars; in urban regions of non-OECD economies, activity on 2-wheelers and public transport is much higher.*

In urban areas of OECD countries, activity is primarily provided by PLDVs. In non-OECD economies, the share of activity provided by urban public transit (buses and rail), albeit declining, is 39%, significantly higher than in OECD countries (16%). Over the past decade, personal vehicles (passenger cars and 2-wheelers) have been responsible for most growth in urban passenger activity, especially in non-OECD economies, which accounted for 88% of the growth. Rising incomes have driven demand for more mobility, as well as the greater comfort and status afforded by personal vehicles. As incomes continue to rise across a wider range of countries and a broader base of their populations, this demand can be expected to keep pace.

As rapid motorisation accompanies rising incomes in the developing world (Sperling and Gordon, 2009), and as travel and car use plateau in rich countries (Goodwin, 2012), total car activity in non-OECD economies has risen to match that in the OECD. This masks a gulf in energy use and mobility per capita, however. Roughly 4.9 times as many people live in non-OECD economies as in OECD member countries, but passenger activity per capita (40%) and energy use (18%) remain far lower in non-OECD economies, where there is a higher share of travel on energy-efficient public transport. As per capita income in non-OECD economies increases, use of personal vehicles will continue to grow. In contrast, personal vehicle activity and ownership in most OECD countries is at or near saturation.

A global overview of urban passenger transport activity shows that 2- and 3-wheelers account for a high share of urban passenger travel in China, India and countries belonging to the Association of Southeast Asian Nations (ASEAN) (Figure 5.2). Canada, the United States and (to a lesser extent) Mexico, Australia and New Zealand depend heavily on cars for urban mobility, and have high shares of large cars. Car travel is also predominant in Europe and the Middle East and, to a lesser extent, in Japan and Russia.

Figure 5.2 **Urban passenger transport activity, 2015**



This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

Note: Around 40% of China's stock of 2-wheelers is electric. The definitions of "Small and medium cars" versus "Large cars" vary by country and region, depending on availability of data and the benefits of disaggregating market segments. EU Nordic is Denmark, Finland and Sweden.
Source: IEA (2016), *Mobility Model,* January 2016 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Key point *Passenger transport activity by mode varies widely from region to region. Countries with high incomes and lower fuel taxes tend to be more dependent on car travel.*

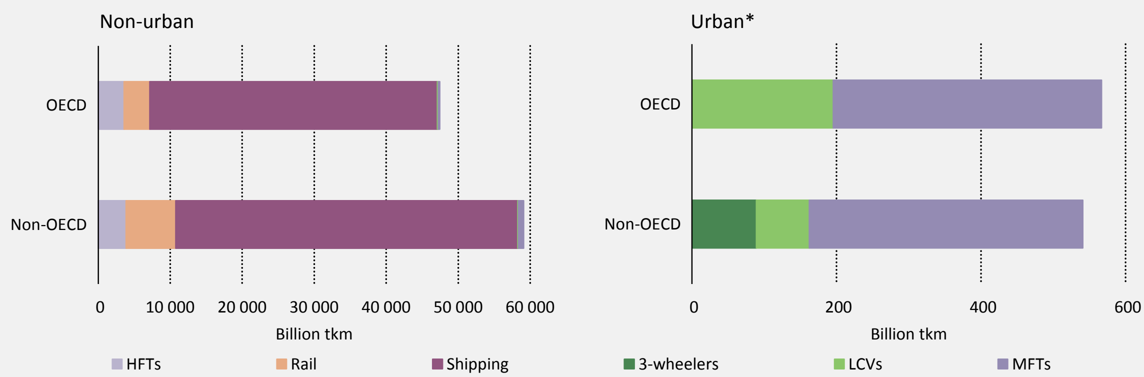
In developing regions, where average incomes and car ownership levels are lower, bus and rail travel are more predominant. The provision of rail infrastructure varies greatly among developing regions; South and Latin America, Africa and ASEAN countries rely primarily on bus travel, but in China, rail accounts for a substantial share of urban passenger transport.

National averages obscure the fact that certain cities across the developed world are global leaders in restricting car ownership (e.g. Singapore); in providing accessible, reliable, fast and convenient public transport (e.g. Berlin and Paris), or walking and cycling infrastructure (e.g. Amsterdam and Copenhagen); and in implementing strong, effective road and cordon pricing (e.g. London and Stockholm). Other cities are test-beds of innovative mobility services (e.g. Helsinki and San Francisco), or pioneers of new financing mechanisms (e.g. Seoul and Tokyo), and of new zoning and regulatory measures designed to lead to densification and public-transport oriented development.

Freight transport activity

Urban freight transport accounts for only 1% of global freight as measured in tonne kilometres, partly because non-urban maritime transport accounts for a large share of global freight (81% in 2015), and partly because urban freight delivery vehicles have small storage capacity and cover short distances (Figure 5.3).

Figure 5.3 **Non-urban and urban freight transport activity, 2015**



* Note that the magnitude of non-urban activity (left graph) is 100 times greater than the scale of urban activity (right graph).
Source: IEA (2016), *Mobility Model*, January 2016 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Key point *Freight transport activity is substantially higher outside urban areas and is primarily maritime.*

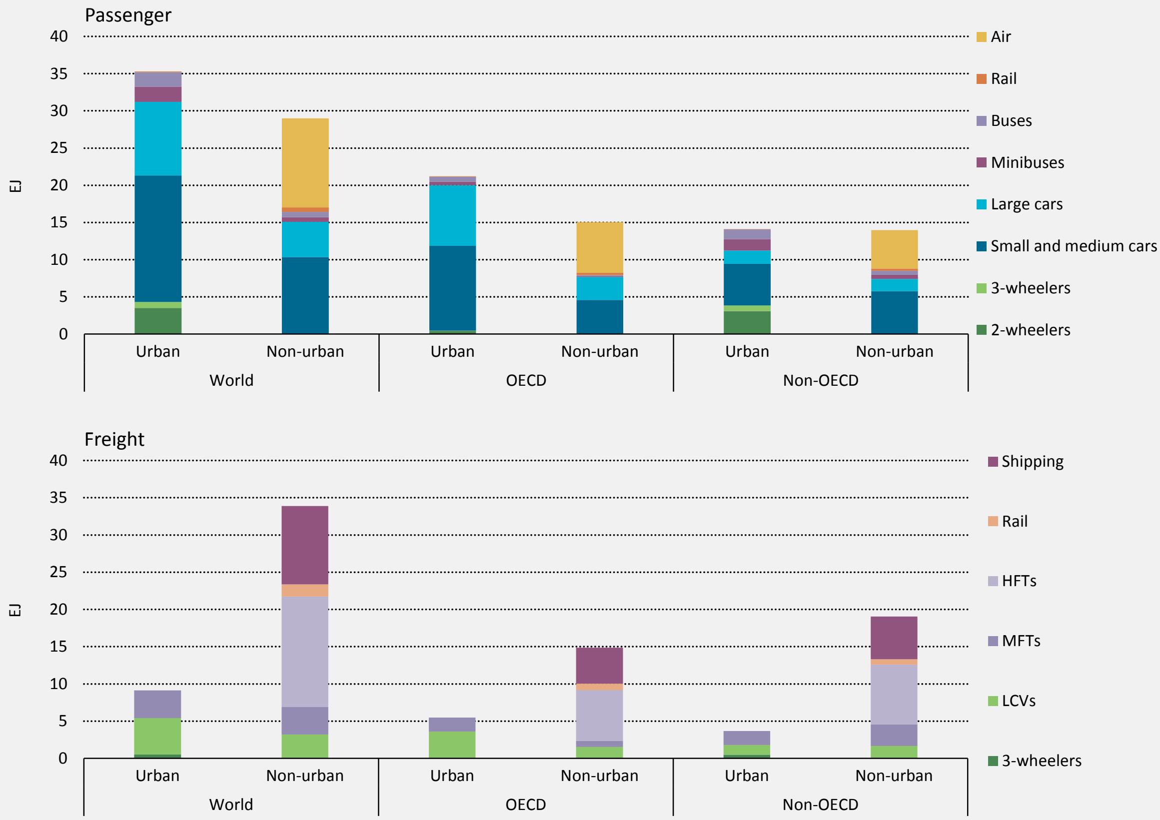
The same elements explain the major differences in urban and non-urban freight transport: ships, trains and HFTs operate exclusively outside urban centres.[8] In both urban and non-urban environments, freight transport activity has grown by 42% to 48% since 2000.

Energy demand and GHG emissions

Passenger services account for 60% of the energy consumption in transport (Figure 5.4) and nearly 80% of transport energy use in urban areas. Cars, followed by aviation, are the main consumers of energy and the main GHG emitters in passenger transport. Cars account for 76% of the global urban energy demand for passenger transport (92% in OECD countries). The next greatest urban energy consumers after cars are freight transport modes, which use slightly more energy than buses and 2-wheelers combined.

8 Freight aviation is not yet included in this analysis, though recent and continuing progress in characterising growing modal activity in air freight may enable its inclusion in subsequent *Energy Technology Perspectives* (*ETP*) publications.

Figure 5.4 Passenger and freight transport energy use, 2015



Source: IEA (2016), *Mobility Model*, January 2016 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

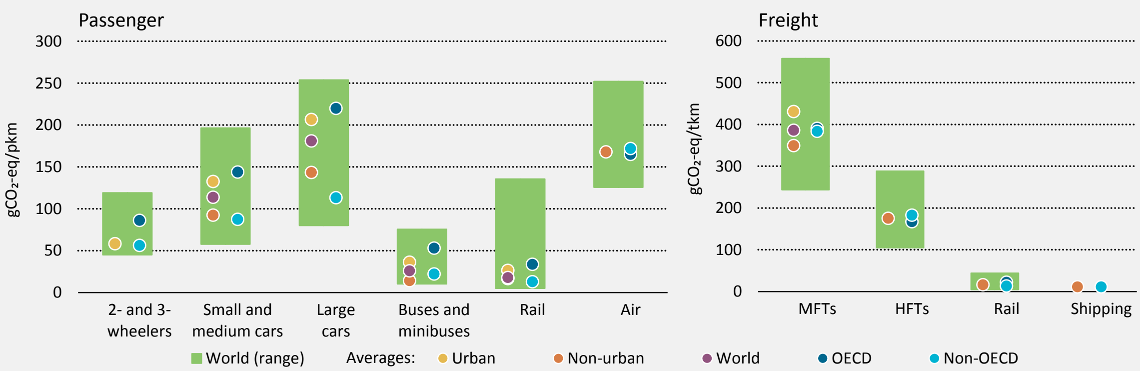
Key point *Urban and non-urban final energy demand for passenger services are comparable on a global level, while freight transport energy demand is significantly higher in non-urban than in urban areas. Passenger transport services account for four-fifths of urban transport energy use.*

Regional differences are significant: in non-OECD economies, the energy used by 2-wheelers exceeds that of LCVs and MFTs, while 2-wheelers represent only a small fraction of urban energy demand in OECD countries. Cars and aviation account for nearly all the energy use for non-urban passenger transport.

Despite making up only 1% of freight transport, urban deliveries consume 21% of energy demand for freight transport, because urban freight modes (LCVs and MFTs) have higher energy and GHG intensities than long-distance freight modes (shipping, rail and HFTs). The GHG emissions intensity of LCVs, for instance, is 3.5 times greater per tonne-kilometre than that of MFTs, which is about twice the intensity of HFTs and more than 10 times that of rail freight. In urban areas, lower speeds, more traffic, and more starts and stops also increase energy and GHG intensities across all modes (also shown in Figure 5.5).

GHG intensity varies substantially from region to region. The discrepancy in mean emissions intensity between OECD member countries and non-OECD economies is most apparent in personal passenger cars. This is due to lower vehicle occupancy and larger average vehicle sizes in OECD countries.

Figure 5.5 Well-to-wheel GHG intensities of passenger and freight transport activity, 2015



Note: gCO_2-eq/pkm = grammes of CO_2 equivalent per passenger kilometre. World, OECD and non-OECD values are weighted averages of the regions covered in the International Energy Agency (IEA) Mobility Model. The GHG emissions intensity ranges reflect the variation observed across all regions. Urban and non-urban refer to global averages. LCVs (not shown in the freight transport section of this figure for readability) have a GHG intensity 3.5 times higher than that of MFTs.
Source: IEA (2016), *Mobility Model*, January 2016 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Key point *There is significant disparity in transport GHG emissions intensity across world regions and urban and non-urban areas. Cars and airplanes are the most GHG-intensive modes in passenger transport. Trucks are the most GHG-intensive modes in freight transport (freight aviation is not assessed here).*

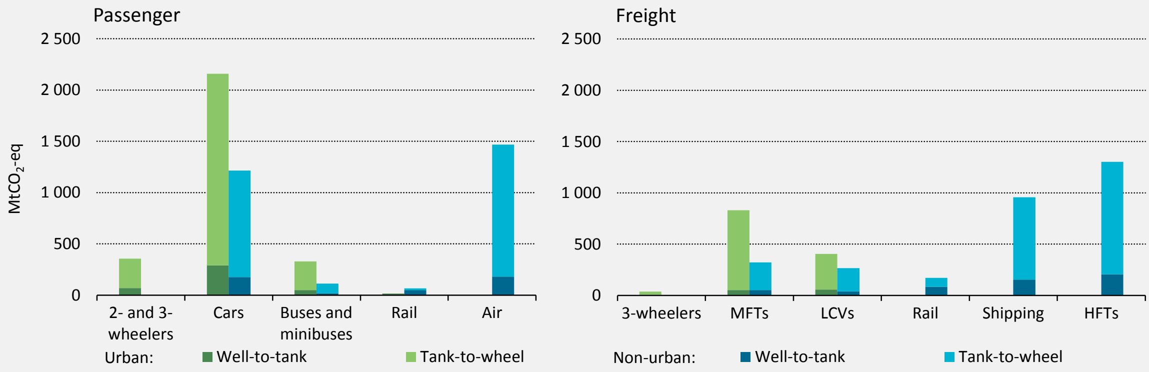
In 2015, transport-related well-to-wheel[9] GHG emissions reached 9.1 $GtCO_2$-eq. Of these emissions, 40% resulted from urban activity, 58% from passenger transport and 84% from combustion of fuels by transport vehicles (tank-to-wheel emissions) (Figure 5.6).

For transport modes that rely primarily upon petroleum products, the ratio between tank-to-wheel and well-to-tank GHG emissions mainly reflects the conversion losses taking place in refineries, where crude oil is converted to oil products; in the case of biofuels, it reflects the emissions due to the production and harvest of feedstocks, as well as their conversion to liquid fuels. Rail is the only transport mode with a higher share of well-to-tank GHG emissions. This is primarily explained by the much higher electrification rate of rail, and is more relevant in urban rail, which is nearly all electric.

Unless measures are implemented that reduce GHG emissions from the production of fuels and that decarbonise the production of other energy carriers, the proportion of well-to-tank emissions is set to grow, driven by changes in the supply share of light oil and heavy oil, and in the power generation mix.

9 This section distinguishes between GHG emissions from production and distribution of transport fuels – from the extraction of primary feedstocks to the delivery to the final site of distribution to the end user (well-to-tank) – and emissions occurring during the combustion of the fuels by vehicles (tank-to-wheel). The total of these two makes up well-to-wheel GHG emissions. This does not include emissions from vehicle or battery manufacturing, nor those offset by material recycling, among others.

Figure 5.6 GHG emissions from passenger and freight transport activity, 2015



Note: $MtCO_2$-eq = million tonnes of CO_2 equivalent.
Source: IEA (2016), *Mobility Model*, January 2016 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Key point *Since oil is the main fuel source for transport, most GHG emissions take place at the tailpipe of vehicles.*

Projections of transport activity, energy use and GHG emissions

Historic data on urban and non-urban personal vehicle ownership and mileages, as well as the share of transport activity that takes place in personal vehicles (compared with the total activity of personal vehicles and public transport modes), were mapped against income levels for all world regions. The resulting maps were combined with projections of key socio-economic drivers (population, population density, gross domestic product [GDP] and urbanisation rates) to develop projections of passenger urban and non-urban transport activity. Similar relationships were used to project the growth of freight transport.

Activity projections were then integrated with vehicle stock models and energy intensities for vehicle and powertrain technologies in each mode to estimate energy demand. GHG emissions result from the combination of energy demand by energy carrier, fuel properties (for tank-to-wheel estimation), and well-to-tank emissions factors of energy carrier production pathways.

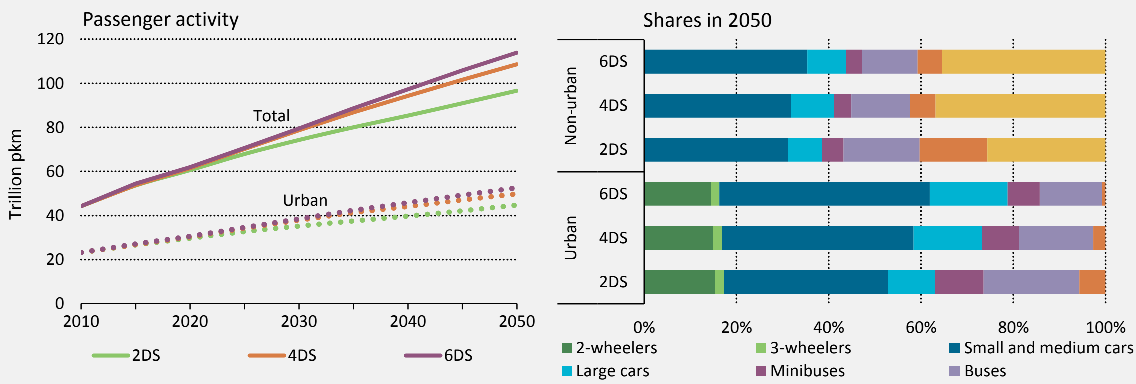
The disaggregation of activity into urban and non-urban designations of PLDVs and buses in passenger transport, and LCVs and MFTs in freight transport, was performed using a combination of assumptions and methods, such as the methodological choices made for the modal allocations, regression analyses and Geographic Information System (GIS) methods. GIS methods were applied to characterise urban regions with differing densities and to delineate urban areas suitable for the deployment of high-capacity public transport. Regressions were used to fill data gaps, for example by combining comprehensive information available in specific records with datasets having a wider geographical coverage, but also a lower degree of detail.[10] Details of the methods

10 The two main data sources were the *Rapid Transit Database* of the Institute for Transportation and Development Policy (ITDP, 2015) and the International Association of Public Transport's *Millennium City Databases* (UITP, 2015).

used to disaggregate urban and non-urban vehicle stock, activity and specific energy intensity are provided in Annex F.[11]

To meet the needs of a growing global population with increasing incomes, demand for passenger transport is projected to rise in all three scenarios – 2DS, 4DS and 6DS. In the 2DS, total passenger activity grows by 80% from 2015 to 2050, from 54 trillion pkm to 97 trillion pkm (Figure 5.7). In the 4DS and 6DS, global passenger activity exceeds 100 trillion pkm in the 2040s. Travel is lower in the 2DS because of substantially higher fuel prices; higher vehicle taxes for cars; and densification policies (Box 5.3) that shorten the length of trips, provide incentives to forgo or chain trips, and promote shifts to public transport, walking and cycling.

Figure 5.7 **Total and urban passenger transport activity by scenario and shares in 2050 by mode**



Source: IEA (2016), *Mobility Model*, January 2016 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Key point *Passenger transport activity is expected to – at minimum – nearly double by mid-century. In the 2DS, urban passenger activity shifts from cars to public transport and, to a lesser extent, to 2- and 3-wheelers. Non-urban mobility shifts from air to high-speed rail and from passenger cars to intercity buses and rail.*

Across all three scenarios, urban travel's share of total transport activity declines from about 50% in 2015 to 46% in 2050, primarily because demand for long-distance travel grows more rapidly than demand for urban transport.

Personal vehicles represented about 69% of global urban passenger activity in 2015. This share declines by 6% in the 2DS and increases by 4% in the 4DS and by 10% in the 6DS. In the 2DS, passenger car use is replaced by buses, metropolitan and suburban rail, and 2- and 3-wheelers as a consequence of comprehensive and co-ordinated policy actions (see policy section below).

Total freight activity grows by about 55% from current levels by mid-century, from 108 trillion tkm in 2015 to 167 trillion tkm in 2050, with little difference across scenarios.[12] The urban share of freight remains steady despite the growing proportion of urban

11 The methodological annex for the transport analysis conducted for *ETP 2016* is available at www.iea.org/etp/etp2016/annexes.

12 Implications of policies on total freight activity as mediated through changing trade patterns, as well as reduced demand leading to lower shipping volumes of fossil fuels and their products – e.g. coal, crude oil and liquefied natural gas (LNG) – are not currently tracked.

residents. Shipping continues to dominate non-urban freight activity in all scenarios. As developing and emerging economies grow richer, the share of 3-wheelers (which operate primarily in developing countries) declines in all scenarios from 8.2% of urban freight to around 4.7% in 2050 as they are replaced by LCVs.

Energy efficiency and energy diversification measures in trucking, together with continuing advances in logistics, enable reductions in energy use and GHG emissions. In urban regions, this is accomplished by the progressive introduction of fuel economy standards and access restrictions favouring electrification in road freight vehicles. In long-distance heavy-duty trucking, efficiency standards drive innovations in aerodynamics and vehicle design as well as more fuel-efficient engines. The electrification of heavy-duty trucks is confined to specific applications (e.g. at ports, inland ports and dedicated routes) and does not play a major role. This increases the need to substitute diesel in heavy-duty trucks with alternative fuels, including low-carbon biofuels. Freight scheduling and logistics can provide immediate and substantial GHG abatements (Liimatainen et al., 2012; McKinnon, 2012).

The energy supply mix varies from region to region, but by 2050 it is more diverse than in 2015 in urban and non-urban regions and in all scenarios (Figure 5.8). The diversification is far greater in the 2DS. The overall (urban plus non-urban) share of transport fuels derived from sources other than fossil fuels increases from 6.4% (mostly biofuels) in 2015 to 41.4% in the 2DS, 13.8% in the 4DS and 11.8% in the 6DS. Electricity generated in the 2DS by renewable generation technologies (wind, water, solar) and low-carbon biofuels have the best prospects as low-carbon substitutes for oil-based fuels. Natural gas and biogas may become viable substitutes in medium-duty and heavy-duty trucks, as well as in shipping, provided that methane emissions are avoided.

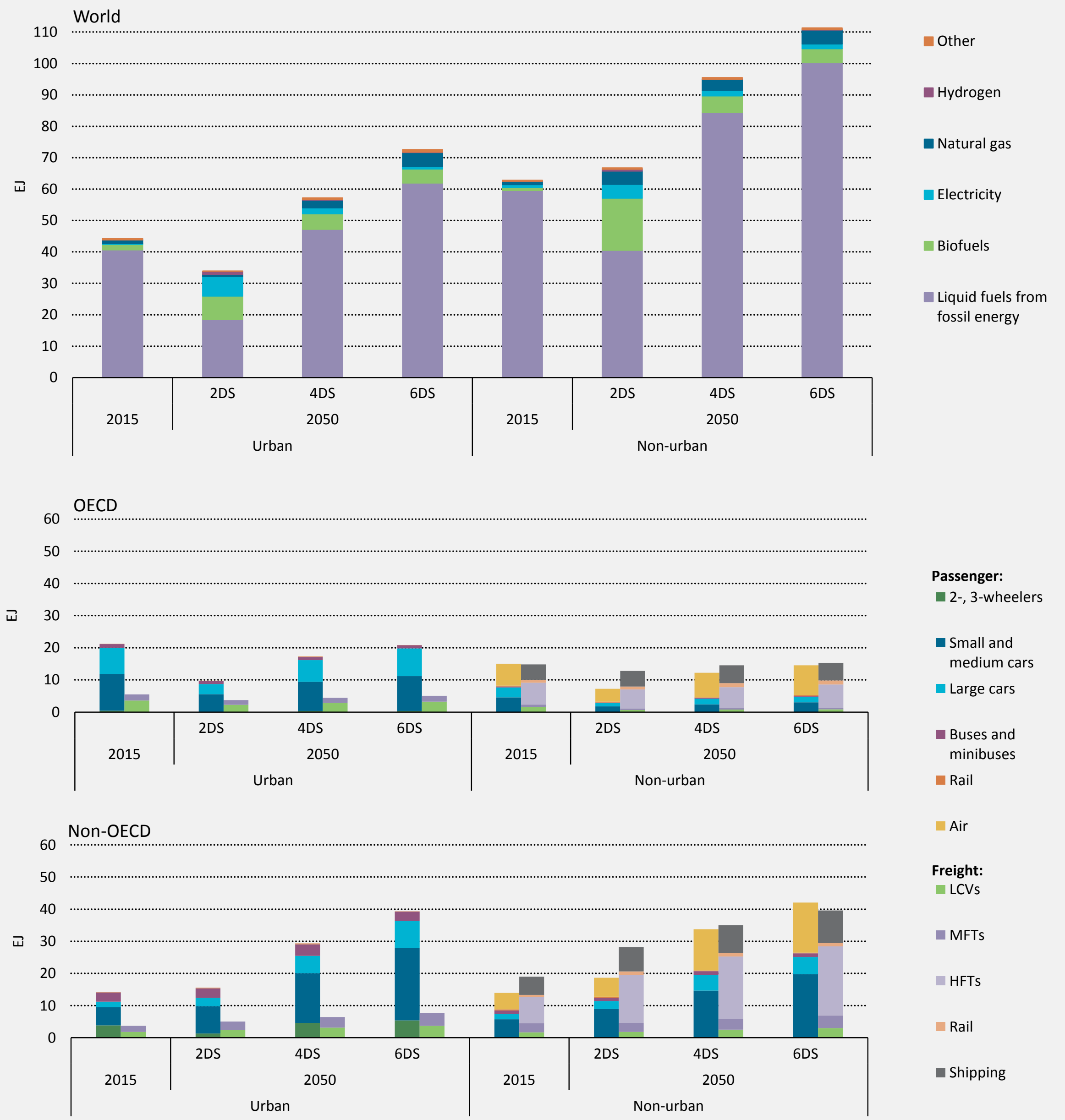
Notwithstanding the potential for substantial cost reductions for hydrogen fuel cells in vehicles, long-term prospects for hydrogen fuel-cell electric vehicles (FCEVs) are limited, even in the final decade of the 2DS, by the availability of low-cost excess electricity from variable renewables. This reflects the investment risks of shifting to centralised hydrogen production and building up an adequate hydrogen distribution infrastructure.

Aside from the shift in fuel sources, major differences in total energy use in 2050 distinguish the scenarios. Both passenger and freight energy use, in both urban and non-urban settings, stabilise (in 6DS) or decline (in 4DS, and even more in 2DS) relative to 2015 in OECD countries. Energy demand continues to rise in non-OECD economies, albeit at varying rates across scenarios. Achieving energy savings is especially challenging in non-urban freight transport.

The total amount of energy consumed by cars is the main element distinguishing the 2DS, 4DS and 6DS in urban transport, in both OECD and non-OECD economies. In the 2DS, vehicle efficiency gains are stronger and vehicle stocks smaller across urban and non-urban areas, as a result of a wide range of policy measures, including higher fuel and vehicle taxes; more stringent fuel economy standards; local measures favouring electric vehicles (such as waivers on parking fees and tolls, access restrictions and low-emission corridors, and provision of public charging infrastructure); pricing and compact city policies that reduce urban trip distances; shifts in investment decisions; and financial support for public transport and non-motorised modes.

In OECD countries, urban transport-related GHG emissions have peaked; even in the 6DS, 2050 emissions do not exceed 2015 levels. Urban transport emissions in 2050 are 62% lower in the 2DS than in the 4DS and 69% lower than in the 6DS (Figure 5.9). The cumulative emissions abatement achieved over four decades in the 2DS ranges between 23% (if calculated against the 4DS) and 31% (against the 6DS).

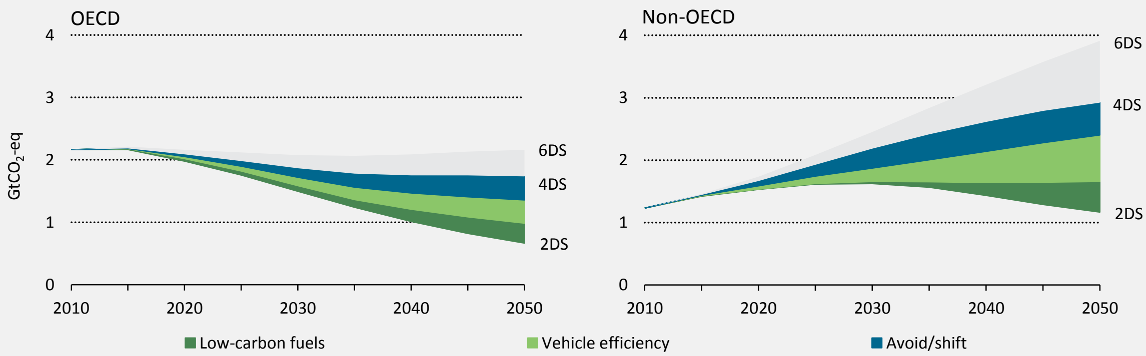
Figure 5.8 Final transport energy demand by scenario



Source: IEA (2016), *Mobility Model*, January 2016 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Key point *The 2DS requires the diversification of energy carriers, a decline in urban energy demand and a stabilisation of non-urban energy demand. The increases in energy use occurring in passenger air transport and heavy trucking highlight a long-term challenge for mitigating GHG emissions of these modes.*

Figure 5.9 **Well-to-wheel GHG urban abatement potential in OECD and non-OECD economies by scenario**



Source: IEA (2016), *Mobility Model*, January 2016 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Key point *Urban transport emissions stand to decline in OECD countries and can be stabilised by 2050 in non-OECD economies, by strong across-the-board measures. Abatement potential in developing urban areas is considerable and so must be prioritised.*

Urban GHG emissions grow rapidly in non-OECD economies as wealth and urbanisation increase. In all scenarios, urban GHG emissions in non-OECD economies surpass those in OECD countries before 2030. The potential to reduce GHG emissions in percentage terms is roughly the same in OECD and non-OECD economies (GHG emissions in the 2DS in 2050 are 60% to 70% lower than in both 4DS and 6DS), but the cumulative abatement potential in absolute terms (in million tonnes of CO_2 equivalent) is about 60% greater in non-OECD economies than in OECD countries.

In OECD countries, more than a third of the abatements are achieved through measures that lead urban residents to avoid trips and shift them to public transport (e.g. through increasing the costs of owning and operating a car, via urban densification combined with travel demand management). Another third of the GHG emissions savings stem from gains in vehicle efficiency (i.e. due to improvements in internal combustion engines (ICEs), drivetrain hybridisation and electrification), and the remaining share of GHG abatement comes from growing use of low-carbon fuels.

In urban areas in non-OECD economies, the potential to reduce emissions via avoiding/shifting high GHG intensity activities and through vehicle efficiency measures is higher (36-41% for each) than in OECD countries. The increased relevance of avoid/shift can be explained by the fact that many cities in non-OECD economies have not yet “locked in” to dependence on cars, and hence may develop along widely diverging trajectories, depending on local policies. Particularly for cities in the developing and emerging world that have yet to be built, there is considerable flexibility for urban form and transport infrastructure to guide behaviour. The structure of car fleets in markets of non-OECD economies explains much of the potential for vehicle efficiency to drive rapid and considerable GHG abatement. First, a low baseline fuel economy, especially in freight truck fleets, implies more room for improvement. Second, vehicle efficiency gains translate to faster improvements in fleet-wide fuel economy in countries where the share of new vehicle registrations in rapidly growing fleets is higher – as is or will be the case in many vehicle markets in non-OECD economies.

The potential for low-carbon fuels (primarily electrification) is lower (18-27%) in non-OECD economies than in OECD countries. This reflects the higher costs, and hence slower diffusion, of technologies enabling energy supply diversification in urban settings (such as electrification) and of alternative fuels (e.g. advanced biofuels and methane/biomethane) in long-distance transport modes such as aviation and road freight.

There is substantial regional variation in capacity and level of ambition to decarbonise transport at the national, provincial and municipal levels. For instance, Nordic countries have set targets to decarbonise the sector completely by mid-century (ENS, 2013; OECD, 2011; OECD, 2014a; and OECD, 2014b).

Technologies enabling the transition in urban transport

Delivering the changes required by the 2DS will require deploying technologies that can help manage travel demand (avoiding travel needs and shifting mobility to the most efficient modes), improve the energy efficiency of vehicles, and reduce the carbon intensity of fuels.

Technologies enabling the management of travel demand

Information and communication technologies (ICTs) play a key role in effective travel demand management. They can provide information on the location and availability of parking options for car-sharing and bike rental systems; on the pickup location and time of carpooling users; and on real-time schedules for public transport. They can also improve the way public transport meets demand, for example by monitoring the flow of passengers at different times. Innovative services that provide information on travel times and congestion, typically based on geo-localisation devices, can enhance the convenience, speed and connectivity of intermodal urban public transport systems – but only if public operators and private companies alike are willing or required to share data that they often treat as proprietary.

Automatic number plate recognition, and automatic identification and data capture (AIDC), can provide personal identification and enable pricing mechanisms such as real-time variable congestion charging and measures to regulate access to segments of the road network. Such measures will function most effectively when AIDC and geo-localisation are applied jointly. AIDC complemented by real-time GIS can enable seamless multimodal door-to-door travel, even across borders if there is co-ordination among supra-national, national and local transport authorities. AIDC can also make it possible to trace goods in real time and promote cleaner, more efficient freight transport. ICTs can be used not only to make transport run more efficiently but also to increase comfort, convenience and certainty for transport users (Box 5.1).

Technologies promoting the energy efficiency of transport vehicles

Road transport

Technologies that augment the energy efficiency of road transport vehicles include material substitution (particularly when it leads to weight reduction), tyres with low rolling resistance, advanced lubricants, improved aerodynamics, exhaust heat recovery devices, and powertrains with lower energy consumption per unit load. Optimising engine-fuel combinations and developing more clean-burning fuels may not only reduce local pollutant emissions but also improve efficiency.

Box 5.1 ICTs can optimise transport efficiency

Intelligent transport systems (ITS) is a catch-all for diverse ICT systems applied to transport. ICTs include applications for traffic signals, such as communications systems; adaptive control systems; traffic-responsive, real-time data collection and analysis; and maintenance management systems. An increasing number of pilot and full-scale projects around the world demonstrate the significant fuel savings and GHG reduction potential of these technologies.

Optimising border crossings

Bottlenecks at the Canada-United States border often leave cars idling for long periods. A project at the Peace Arch border crossing initiated in 2008 uses real-time traffic data analysis to control signals that move waiting traffic in a series of pulses, allowing motorists to reduce idling. The project has saved nearly half a litre of fuel per vehicle on each trip, corresponding to a 45% reduction in GHG emissions by the 3 million vehicles that travel across the Peace Arch border annually. The wait time is unaffected, motorists save fuel and money, and 1.9 $MtCO_2$ are abated annually (BC, 2008).

Making fleets more efficient

The Smithsonian Institution operates a fleet of 1 500 vehicles in more than 80 countries. Through a fleet management information system and telematics (which combines Global Positioning System [GPS] tracking and information networking), the Smithsonian has reduced the number of light-duty vehicles in its fleet by 18%. By improving logistics (e.g. chaining trips and running with higher average loads), the system has enabled fuel consumption reductions of 52% since 2005 (Shaw, 2014).

Promoting public transport

Public transport information systems are widely deployed in Korea. Seoul has more than 9 000 on-bus units equipped with wireless modems and GPS position detectors. Bus stops communicate wirelessly with Seoul's central traffic operations management centre to provide an integrated, up-to-the-second view of the bus network, including bus arrival time, current bus location and system statistics. Passengers can use GPS-enabled smartphones to access a list of available public transport options; the system recognises where the passenger is located and provides walking directions to the nearest option.

Digital maps and connectivity

Plug-in hybrid electric vehicles (PHEVs) use 30% to 60% less fuel than conventional vehicles in urban driving. However, managing fuel and battery energy consumption is critical for the fuel efficiency and usefulness of PHEVs; their all-electric range is short (current models are in the tens of kilometres [km], and up to 70 km in the Chevrolet Volt), so power must be sourced mainly from their ICEs on longer trips. Research at Argonne National Laboratory shows that fuel consumption can be reduced by co-ordinating power sourcing between batteries and engines, by using digital maps with real-time updates to predict the speeds, stops and starts, and even hills along a vehicle's itinerary. Efficiency is enhanced by allocating engine operations throughout the trip and targeting battery use for acceleration patterns where the electric powertrain is most efficient, all the while targeting a nearly depleted state of charge for the battery at the trip's end. Particularly on longer trips, the ITS developed by Argonne researchers can enable fuel savings of 5% to 15% (Karbowski, Sokolov and Rousseau, 2015).

Several powertrain technologies may enable energy savings:

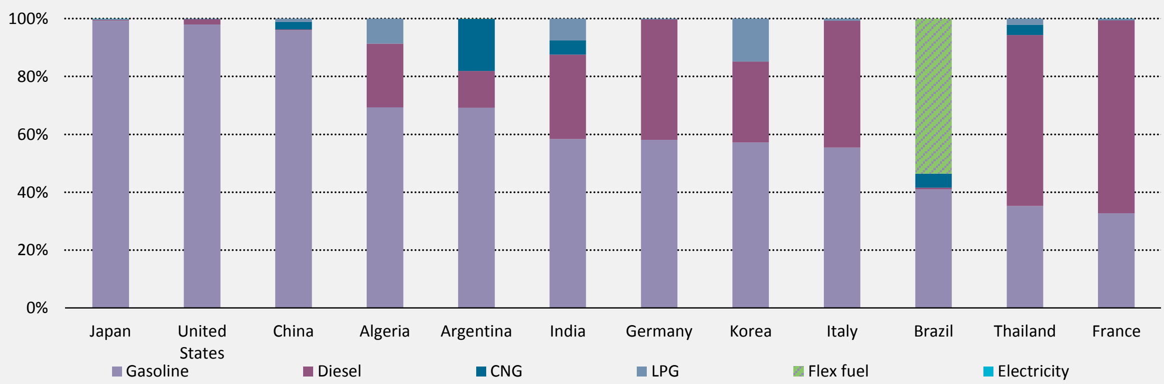
- design modifications improving combustion characteristics of ICEs (primarily in land transport) and gas turbines (mainly in aviation)
- hybridisation of powertrains, for example by combining ICEs with electric motors to improve the load profile of ICEs, while enabling more efficient use and engine switch-off at standstill
- electrification of powertrains.

Electrification combines the high efficiency of electric motors with different energy storage options. Electric vehicles (known collectively as EVs) include battery-electric vehicles (BEVs), which use electricity storage (or other forms of electricity supply, such as overhead power lines) to power electric motors; PHEVs, which combine plug-in electric (battery) storage and a conventional ICE running on fossil fuels; and FCEVs, which use electric motors together with fuel-cell systems and hydrogen storage.

The current uptake of powertrains differs across modes. Spark-ignition ICEs are most widespread in transport modes with low mileages (primarily 2-wheelers and cars). Diesel ICEs, which require higher up-front investments than spark-ignition engines in exchange for better fuel efficiency, primarily equip road transport vehicles with high mileages, such as trucks, LCVs and trains. International marine shipping relies primarily on marine ICEs, while gas turbines are the primary choice for aviation.

The mix of powertrains used in cars differs from region to region (Figure 5.10). The share of diesel ICEs is high in Europe, India and Korea but much lower elsewhere. Countries have encouraged the spread of vehicles that can use alternative fuels through policies such as support for fuel distribution infrastructure, preferential fiscal treatment for alternative fuels, and incentives for using alternative fuels for fleets. This is the case for flex fuel and ethanol cars in Brazil; liquefied petroleum gas (LPG) vehicles in Italy, Japan, Korea, Poland, Russia, Thailand and Turkey; and compressed natural gas (CNG) vehicles in Argentina, Bolivia, Brazil, China, Colombia, India, Iran, Italy, Pakistan and Thailand. Overall, high use of diesel ICEs has generally been coupled with better fuel economy (GFEI, 2016).

Figure 5.10 **Shares of powertrain configurations in PLDV stocks in selected countries, 2013**



Source: IEA (2016), *Mobility Model*, January 2016 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Key point *Penetration of powertrain technologies varies across national car markets as a result of different policies, prices and consumer preferences.*

Little comprehensive information exists on the distribution of powertrains between urban and non-urban areas. Powertrains that cost more than spark-ignition ICEs are more likely to be used for high mileages (see, for instance, Bodek and Heywood [2008] for diesels in France and Germany). Since urban mileage tends to be lower than in non-urban areas, diesel cars are less likely to be used in cities (except for taxi services). The same observation could be extended to cars using natural gas and LPG, but this is counterbalanced by the higher number and proximity of refuelling points likely to be available for urban vehicles using alternative fuels.

Conventional ICE improvements will continue to play a major role in increasing energy efficiency, especially in the short term. For cars, efficiency gains will come initially from gasoline and diesel ICE technologies. From 2005 to 2013, the fuel economy of new vehicles sold worldwide improved by 2.0% per year on average (GFEI, 2014). To meet the 2DS, this rate of improvement needs to exceed 3% through 2030 (GFEI, 2014) and continue to improve between then and 2050. This requires growing market penetration by technologies with larger fuel-saving potential than ICE improvements, including hybrid and electric powertrains.

Recent attention to wide discrepancies between tested and real-world emissions of local pollutants (especially nitrogen oxides) from diesel ICEs, as well as the classification of diesel exhaust as carcinogenic (IARC, 2012), may influence policy decisions and reduce sales of cars with compression-ignition ICEs. Even if car shares of diesel ICEs were to remain constant across national markets, the global share of cars running on diesel will decline as they will represent progressively lower shares of the global market. Increasing dieselisation is unlikely, with consumer preferences impacted by recent discoveries surrounding the control of emissions of local air pollutants from diesel ICEs.

Hybridisation, which has recently become increasingly cost-competitive, is set to gain market share and stands to benefit from the difficulties faced by diesels. Hybrids offer superior fuel economy and lower emissions of local pollutants, and have already been successfully deployed, especially in urban taxi fleets. They are therefore well placed to become one of the preferred options for car manufacturers to comply with stricter regulatory frameworks for local pollutant emissions together with wider global coverage and tougher fuel economy standards. Hybrids are particularly promising in urban contexts, where they offer the best near-term prospects for improving efficiency and reducing local pollutants. Urban truck fleets – such as postal carriers and municipal waste collection – may also benefit from hybrid powertrains.

Prospects for using methane (natural gas or low-carbon biogas) in transport depend on the availability of a secure and cost-effective supply, which varies from region to region, as well as an adequate fuel distribution infrastructure. Natural gas engines may equip light- and heavy-duty road vehicles and have the capacity to reduce local pollutant emissions (namely particulate matter and nitrogen oxides). The GHG abatement potential of switching from diesel to methane obtained from fossil natural gas is limited (about 20% below diesel), although further GHG mitigation can be achieved using biogas. In addition, reducing GHG emissions by switching to methane-powered vehicles requires minimising methane leaks. Leaks may occur from storage tanks as well as from exhaust emissions resulting from incomplete combustion of methane in the engine (“methane slip”). Avoiding methane slip requires deploying specific technologies, ranging from combustion improvements to after-treatment of exhaust gases with catalysts.

Strong policy support will initially be needed to increase market shares of EVs, but growing market shares can progressively reduce technology costs (see Box 5.2). BEVs are well suited for deployment in car-sharing programmes and urban driving, typically characterised by short trip distances. They are also suitable for conventional vehicle ownership models, primarily in cities, where range requirements are lower and recharging points more available. PHEVs and FCEVs are better suited to suburban and non-urban dwellers, who generally make longer trips, and regions with mileages above the global average. The flexibility of PHEVs may make them more suitable than BEVs as the primary choice for households owning a single vehicle.

Box 5.2 Recent developments and prospects for the cost of EVs

Current production costs for EVs are higher than those of ICE vehicles with comparable performance. For BEVs and PHEVs, this is mainly due to the substantial cost of electric energy storage. In the case of FCEVs, the costs are driven up by the fuel-cell system and the hydrogen storage tank. Charging times need to be reduced and an adequate energy supply infrastructure developed. Electric vehicles are also limited by low energy density and low durability of batteries.

Energy densities of passenger vehicle batteries have doubled in the past five years, but remain below 200 watt-hours per cubic decimetre (Wh/dm^3) (Howell, 2014). Another doubling is necessary to meet the 400 Wh/dm^3 energy density target set by the US Department of Energy (US DOE) (US DOE, 2012). Battery costs fell by roughly 20% per year between 2008 and 2014, to around USD 300 per kilowatt hour (kWh) to USD 350/kWh (Nykvist and Nilsson, 2015). General Motors announced that battery costs for their 2016 Chevrolet Bolt had fallen to USD 145/kWh by October 2015, and that they hope to reduce costs below the USD 100/kWh mark by 2022 (GM, 2015). The electric car manufacturer Tesla aims to break the USD 100/kWh mark by 2020 (hybridCARS, 2015).

Battery costs have fallen more rapidly than researchers and analysts initially expected (Nykvist and Nilsson, 2015). Further reductions are needed to reach the US DOE 2022 target of USD 125/kWh – a level that would make PHEVs as affordable as baseline gasoline-powered cars in the United States (US DOE, 2015). Ambitious manufacturing developments announced by premium electric carmakers and battery manufacturers, who aim to double production of lithium ion batteries over 2013 levels by 2017 (Tesla, 2014), bode well for cost savings. New chemistries, such as aluminium-ion, may enable further cost reductions.

For FCEVs, the potential for cost reductions resulting from mass production of fuel cells is significant. Containing costs of mass-produced, high-pressure hydrogen storage tanks is likely to be more difficult, as these costs are largely determined by prices of composite materials, and so only marginally benefit from cost savings stemming from economies of scale (IEA, 2015b).

In the long term, and in low-carbon scenarios such as the 2DS, electricity generation is projected to become less carbon-intensive, and battery costs are expected to decline, making EVs an increasingly attractive option for abating CO_2 emissions in transport.

Uncertainties remain because of the lack of technology maturity, limited commercialisation to date, and consequently scarce experience with consumer preferences. But the assessment of long-term car costs suggests that the cost gap may fall to about 10% of the cost of a conventional car with an improved spark-ignition ICE – well below the range currently faced by consumers considering the purchase of a car or LCV.

The relatively narrow range characterising the cost of competing technologies once fully deployed suggests that even if cost differences are destined to play a role, the long-term deployment of vehicle technologies in low-carbon scenarios will continue to depend strongly on policy developments. Fuel and vehicle taxation, for instance, and broader, stricter fuel economy and tailpipe emissions regulations, could push costs of EVs (even including FCEVs) below those of ICE vehicles, while ICE costs may increase due to the need to comply with such standards. The spread of EVs will also depend on differences in consumer needs and preferences – whether buyers are heavy car users, commuters or occasional drivers, for example – and on travel patterns. The annual average mileage of a car in the United States, for instance, is much higher than in Europe or Japan.

Recent sales trends show that EVs are likely to be deployed first in high-income countries, where car ownership is higher, and where incentives are in place such as fuel economy standards, differentiated vehicle taxes, and local policies promoting vehicles with no tailpipe emissions.

Electric vehicles will also need policy support for recharging infrastructure in both urban and non-urban settings. While electrification requires distributed investments (e.g. for the installation of home chargers) that involve several stakeholders, including public administrations, utilities, vehicle manufacturers and consumers, deploying FCEVs requires more centralised policy and investment decisions. This raises investment risks and could limit their deployment. Significant investments are required to transition from distributed hydrogen production to centralised production and distribution, which is necessary to ensure competitive long-run hydrogen costs (IEA, 2015b). Additional investment is required for hydrogen refuelling stations. There are also high risks due to the chicken-and-egg problem stemming from the need to simultaneously deploy new vehicles and fuel infrastructure.

In heavy-duty transport, EVs are better suited for urban driving, with its stop-start traffic and shorter trips than for long-distance freight transport (IEA, 2015b). Heavy-duty diesel engines can already achieve high efficiencies (up to 40%) at constant highway cruising speeds. In addition, there is considerable room for energy efficiency improvements in diesel heavy-duty trucks (e.g. through aerodynamics and friction reductions in tyres and along the drivetrain), as shown by the US DOE's SuperTruck demonstration (US DOE, 2014).

Electrification of public buses could yield several benefits, including GHG and pollutant emissions reduction. To achieve the goal of pollutant emissions reduction in particular, it is important to pursue electrification of urban buses in tandem with shifting passengers from cars to collective urban transport. The electrification of urban buses can build on a combination of battery storage and overhead energy supply (catenary lines), such as those already deployed in trolley buses, notably in Eastern Europe (trolley:motion, 2015). Bus electrification technology currently at demonstration stage uses batteries and supercapacitors in combination with inductive charging and contact-based systems such as articulated arms (Tozzi, 2015). Supercapacitors are potentially lightweight and cost-effective, and allow for quicker charging at the bus station, but incur additional costs for associated recharging infrastructure and high recharging frequency.

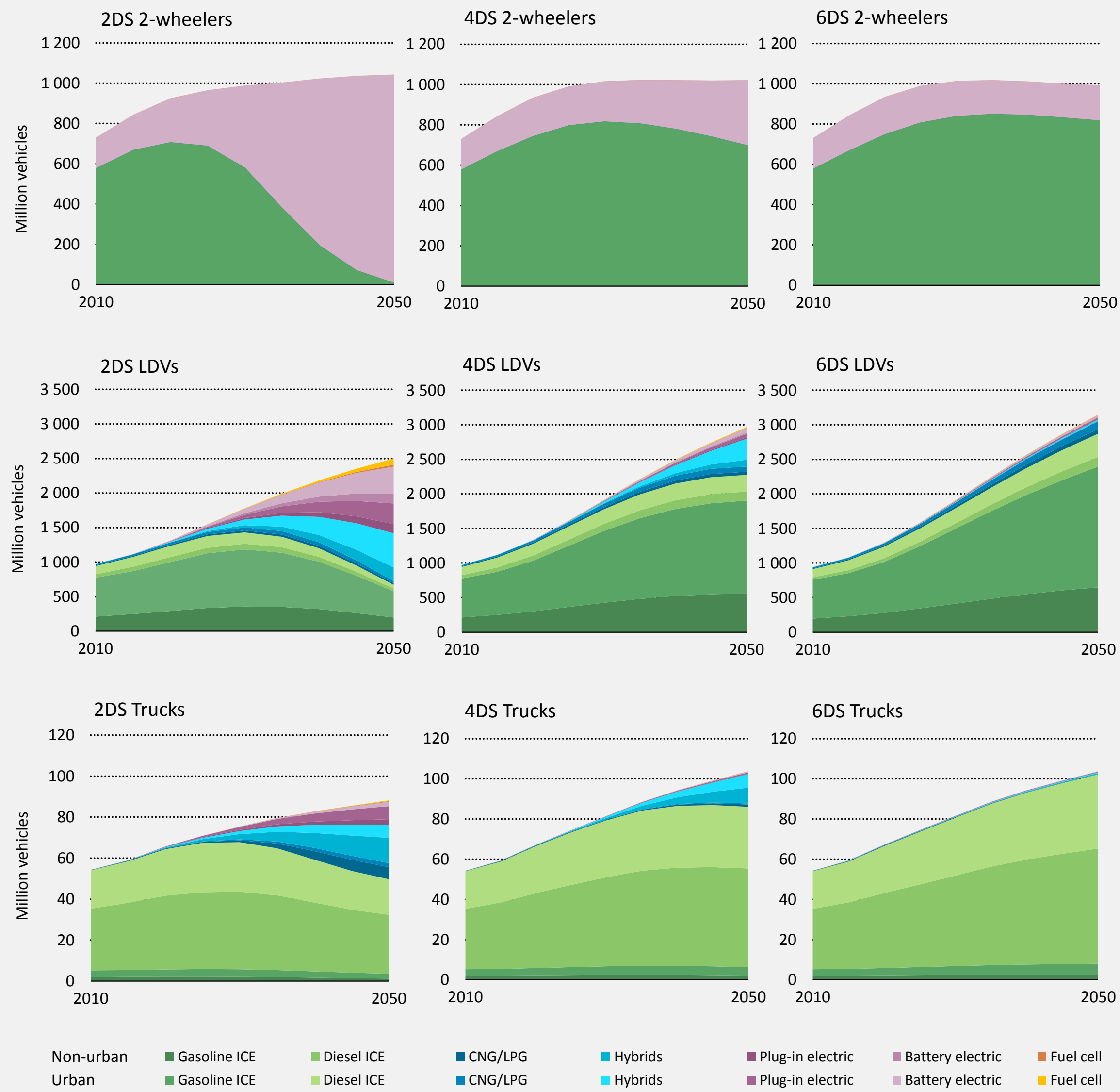
Battery-swapping concepts for buses, emerging in pilot applications, reply upon the potential to recharge at bus terminals (Begins, 2015). This adds battery costs but increases flexibility through larger ranges between charges and offers the potential for integration with variable renewable energy in the electricity grid. Inductive charging technologies may be a way to circumvent the requirements for large batteries in buses and minimise stationary charging times, as tested in demonstration projects in Korea (OLEV, 2015) and the Netherlands (EMOSS, 2012). Electrification of bus fleets could be part of a strategy pursued by public transport authorities that have pledged to become carbon neutral in the time frame 2020-35 (TFGM, 2014; UITP, 2014).

PHEV configurations are more viable for electric trucks in cities. Vehicle electrification in long-distance heavy-duty transport is only possible using a continuous energy supply (e.g. overhead power lines), as already deployed in rail. Road freight applications are currently in the demonstration phase (Siemens, 2015) and will need to be deployed first in local/niche spots (such as mining sites) to demonstrate their wider potential.

Fuel cells could deeply decarbonise heavy-duty road freight transport, but their efficiencies decline with increasing power output and constant speed highway driving requirements. This reduces their competitiveness with ICE or hybrid technologies, unless fuel-cell systems are over-dimensioned, which raises costs (IEA, 2015b). For long-distance transport, hydrogen storage would also require large tanks; even taking into account the higher efficiency of the fuel-cell powertrain, hydrogen stored at 70 megapascals needs four times more space to achieve the same range as conventional diesel technology (IEA, 2015b).

Technology penetration in the three *ETP 2016* scenarios differs widely among passenger modes and between urban and non-urban regions (Figure 5.11).

Figure 5.11 Urban and non-urban vehicle stocks by scenario



Note: LDVs include PLDVs as well as LCVs.
Source: IEA (2016), *Mobility Model*, January 2016 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Key point *Technology deployment varies significantly across modes and scenarios, reflecting different ways to use transport vehicles and taking into account responses to different policy drivers.*

The **2DS** requires significant deployment of innovative technologies across all modes.

- The stock of hybrid light-duty vehicles (LDVs – passenger vehicles plus LCVs) exceeds 115 million in 2030 (6.5% of the fleet) and reaches nearly 700 million in 2050 (28%).
- Hybridisation of trucks occurs more slowly, with hybrids making up 5.4% of the stock in 2030 and exceeding 20% in 2050.
- The entire 2- and 3-wheeler stock becomes fully electrified by 2050. This reflects the competitive costs of electric 2-wheelers (which already cost less than EUR 500 in China) as well as the need to respond to policy signals requiring lower emissions of local pollutants and GHGs.
- The electrification of powertrains becomes widespread in LDVs: the stock of BEVs and PHEVs reaches nearly 160 million by 2030 (nearly 9% of all LDVs), and nearly 1 billion by 2050 (nearly 40% of all LDVs). Highest market penetration takes place in the OECD (namely Canada, Europe – especially the Nordic countries – Japan, Korea and the United States) and in China.
- Electrification is also progressing for heavy-duty road vehicles operating in urban areas, including buses and trucks. In the case of medium trucks, the PHEV stock exceeds 2 million in 2030 (2.7% of all trucks) and 9 million in 2050 (more than 10% of all trucks).
- The share of vehicles using methane as a fuel grows primarily in heavy-duty road freight, representing nearly 2% of the stock in 2030 (but up to 8.5% of new vehicle market share by 2035) and nearly 9% in 2050.
- FCEVs' share of the vehicle stock remains marginal until 2030 and then grows to nearly 5% for LDVs in 2050, when market shares attain nearly 10%. High-income countries witness the highest uptake, reflecting their higher capacity to use risk-sharing instruments to deploy refuelling infrastructure.

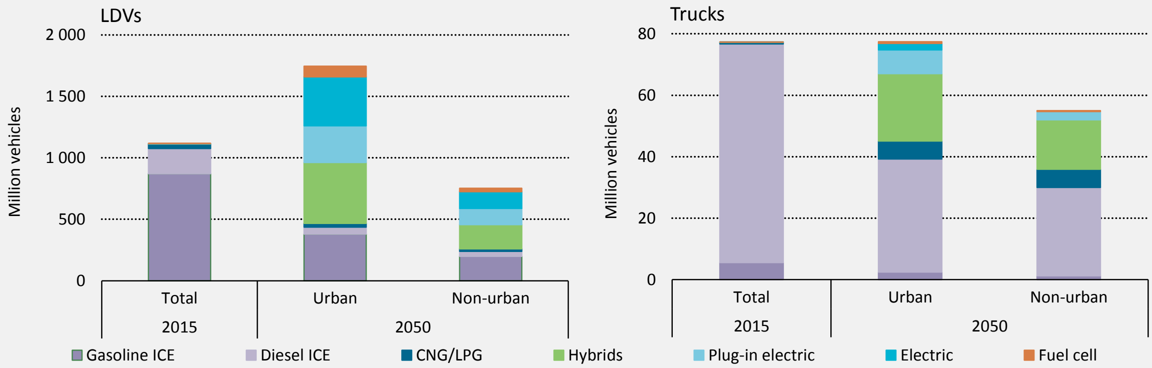
In the 2DS, alongside significant market penetration of hybrids and conventional ICE improvements, EVs are needed to comply with increasingly stringent fuel economy standards. They are supported by differentiated vehicle purchase taxes. Their deployment takes place on the top of the significant market penetration of hybrids and conventional ICE improvements.

The overall share of BEVs, PHEVs and FCEVs is higher in urban than in non-urban areas, but not markedly different (Figure 5.12). Installing charging infrastructure in urban parking spots, garages and apartment buildings faces stronger barriers than installing home chargers in rural areas, but this difficulty is likely to be outweighed by policy pressure to reduce air pollution in urban areas by deploying electric vehicles.

Long-term cost differences between BEVs and PHEVs will depend on trade-offs between vehicle performance (especially range) and costs (primarily electricity storage). In the 2DS, BEVs gain higher shares than PHEVs in cities (while PHEVs gain higher shares in non-urban areas) as battery costs fall and consumers adapt to vehicles that require frequent recharging.

The **4DS** incorporates increasing shares of electric 2-wheelers, not limited to the Chinese market, together with a significant penetration of energy-efficient ICEs. The stock of hybrid LDVs grows to more than 30 million in 2030 and more than 400 million in 2050, primarily driven by the need to comply with fuel economy standards. Efficiency standards drive increased hybridisation of trucks, especially those that make frequent stops. CNG is most relevant in markets where it already has a significant share today, and grows slightly in heavy-duty trucks across all regions.

Figure 5.12 LDV and truck vehicle stocks by technology in the 2DS scenario



Note: LDVs include PLDVs as well as LCVs. Electric powertrains also rapidly penetrate urban bus fleets (not shown).
Source: IEA (2016), *Mobility Model*, January 2016 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Key point *Prospects for vehicle electrification are higher in urban areas than in non-urban areas.*

In the **6DS,** which assumes low oil prices and no additional policies to reduce local pollution and GHG emissions in transport, penetration of advanced vehicle technologies remains low across all modes. The market for electric 2-wheelers is limited almost exclusively to China and to the current shares (as a fraction of passenger vehicles) in all other countries. Hybrids have little market uptake across all modes, and CNG remains a feature of vehicle stocks where it already has a significant share.

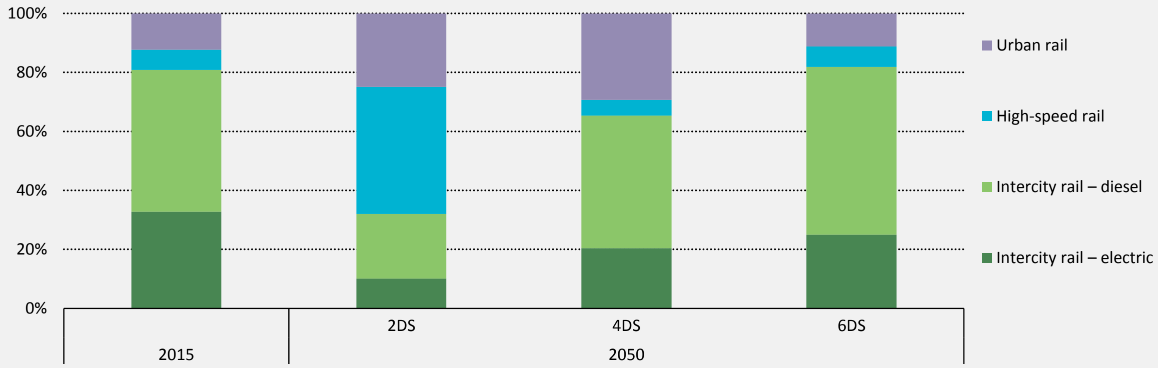
Rail transport

The measures with the best prospects for improving the energy efficiency of trains include material substitution (especially reducing weight), improved aerodynamics, vehicle designs and configurations allowing higher capacity per vehicle, and the use of powertrains with lower energy consumption per unit load (primarily electric motors).

Two-thirds of passenger rail transport activity currently runs on electric trains (Figure 5.13). This includes virtually all urban rail links, all high-speed rail links and most intercity rail activity. Intercity rail track electrification has been primarily justified by lower energy costs of electric trains compared with diesel-powered trains. The deployment of electrification infrastructure for rail tracks typically starts in high-activity rail network segments, where payback periods for initial investment costs are shorter. In urban rail links, the presence of other constraints, such as the need to avoid emission of pollutants in underground lines, drives the dominance of electric trains.

The share of passenger rail activity on electric networks varies widely across *ETP* scenarios. In the 6DS and 4DS, the global share of electric rail increases at rates similar to those in the past few decades. In the 2DS, diesel trains account for only a small fraction of passenger rail travel in 2050 due to rapid growth in fully electric modes: high-speed rail (which replaces some air transport activity) and urban rail (which displaces personal vehicle activity). The 2DS further incorporates higher electrification rates in intercity and regional rail networks.

Figure 5.13 Shares of passenger rail activity by scenario



Source: IEA (2016), *Mobility Model*, January 2016 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Key point *The rate of penetration of electric rail increases from the 6DS to the 2DS scenario, driven by higher shares of urban and high-speed rail, as well as by increasing rates of electrification of intercity and regional rail networks.*

Shifting from oil dependence to low-carbon fuels

Reducing the transport sector's dependence on fossil fuels, and above all on products of petroleum, can be achieved by:

- Shifts in modal relevance (e.g. via increased reliance on rail, the most electrified mode).[13]
- Evolution of the vehicle/powertrain technology mix within a mode (e.g. through increasing shares of CNG [or LNG] trucks, or the electrification of road and rail transport modes, or the deployment of FCEVs, enabling the use of hydrogen).[14]
- Modifications to the shares and supply pathways for producing energy carriers.[15]

This section focuses on the links between urban transport developments and the use of low-carbon fuels and energy carriers. It also outlines the evolution of fuel use in non-urban transport modes. Like all other sections, it concentrates primarily on aspects that characterise the 2DS.

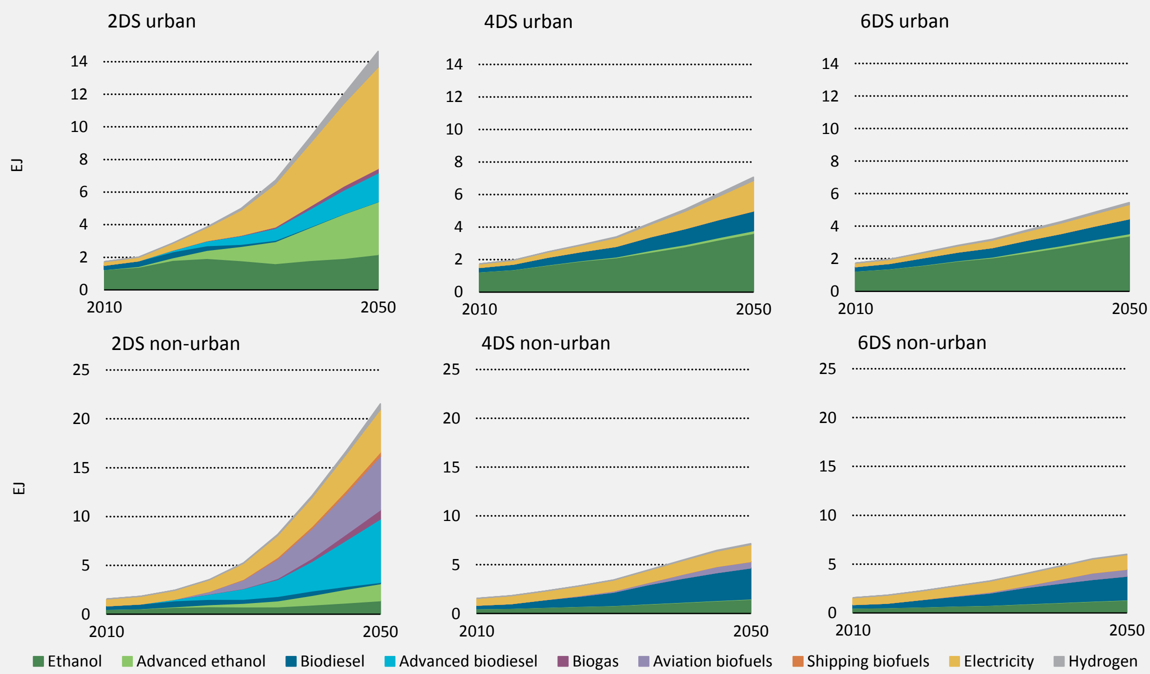
In the 2DS, low-carbon fuels contribute nearly 15 EJ of energy demand in urban transport and more than 20 EJ in non-urban transport (Figure 5.14). In 2050, this represents more than a doubling from the 4DS in urban environments, and roughly a tripling outside of cities. Differences in the total contributions of alternative fuels in 2030 are smaller, reflecting the stronger uptake of alternative fuel vehicles and low-carbon fuels in the longer term in the 2DS.

13 Shifts in modal relevance have been discussed in the section of this chapter illustrating projections of transport activity, energy use and GHG emissions.

14 For a discussion on vehicle/powertrain technology mix within transport modes, and related implications for urban developments, the reader is referred to the section immediately prior to this one, on technologies promoting the energy efficiency of transport vehicles.

15 Modifications to the shares and supply pathways for producing energy carriers have also been partly discussed in other sections of this publication. The decarbonisation of the electricity mix is addressed in Chapter 6 of this publication. The transport section of Chapter 1 provides an update on biofuel production technologies and includes prospects for their deployment in different scenarios. The same section also briefly outlines characteristics of the main hydrogen generation pathways and their contribution to low-carbon scenarios.

Figure 5.14 **Urban and non-urban contribution of alternatives to fossil fuels to meeting transport energy demand by scenario**



Source: IEA (2016), *Mobility Model*, January 2016 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Key point *Electricity, hydrogen and advanced biofuels, supplemented by ethanol from sugar cane, are the main alternative energy carriers in the 2DS. Focusing on biofuels, urban areas see higher contributions from fuels compatible with gasoline, while diesel substitutes are most suitable in non-urban transport.*

Electricity's share of transport energy in passenger cars grows to 20% by 2050, when 59% of total electricity use is in urban settings. Two-wheelers and LDV stocks electrify fastest, but electrification also proceeds rapidly for PHEVs in trucks and across growing urban rail networks. Contributions from electricity are not limited to urban transport in the 2DS. In non-urban transport, electricity demand is driven by increasing activity on high-speed rail, supplemented by the electrification of cars.

In the 2DS, biofuels contribute about half of the energy demand for alternative fuels in urban areas and three-quarters in non-urban areas. For urban transport, biofuels will need to be primarily compatible with gasoline blends, while non-urban transport will need major contributions from biofuels capable of substituting middle distillates (primarily diesel and kerosene). Non-urban transport is responsible for most of the additional biofuel demand in the 2DS beyond other scenarios. Advanced biofuels contribute to the biofuel mix only in the 2DS. In the 4DS, advanced biofuels lack adequate policy and RD&D support and struggle to achieve cost-competitive production, and so do not contribute significantly to transport energy supply.

Hydrogen is assumed to penetrate only slowly in the 2DS, to reach 1.5 EJ by 2050, or about 1.5% of total energy demand. Hydrogen demand is driven nearly exclusively by the deployment of FCEVs among LDVs, primarily in cities, where there are more likely to be refuelling stations and economies of scale that help overcome the barrier of transport and distribution costs.[16]

Policies allowing the transition

To realise the transition to a sustainable future, policy makers need to implement measures that reduce the social and environmental costs generated by transport systems. Such costs include time lost in congested traffic, the health costs of safety hazards and air pollution, changes in property value and health costs due to noise, time losses and access limitations resulting from the separation of urban areas by transport infrastructure, and climate change effects due to GHG emissions.

To make such costs part of the decision-making process of transport users, policy makers need to ensure that they are reflected in end-user prices. The variability across space and time of some of these costs, such as exposure to pollution and congestion, as well as technical and methodological difficulties in the evaluation of some of them, pose significant challenges. Intergenerational issues add further challenges to align private costs with social costs – see, for instance, Goulder and Williams III (2012).

The policy tools available for lowering these costs include market-based instruments (such as taxation or cap-and-trade schemes), command and control measures (such as performance-based regulations), or a combination of these (Korzhenevych et al., 2014).

A combination of policy tools that have already been implemented in certain regions is the best, most pragmatic solution. Combining policy actions provides the flexibility needed to address problems with varying relevance at different administrative levels; for example, degrees of exposure to pollution and varying levels of congestion in metropolitan areas. It also offers the possibility of calibrating measures such as fuel economy standards and differentiated vehicle taxes to bridge the gap between benefits for society and individual choices.[17] To achieve such results, combined measures must be applied coherently.

Table 5.2 summarises policies affecting transport activity, energy use and GHG emissions that will need to be introduced in cities to attain 2DS targets. The table shows in a simplified way how stringently policies are applied in each region. It characterises policies according to administrative level and their main impacts in terms of the key transformations allowing a transition towards more sustainable transport systems:

- managing travel demand to avoid trips or shift travel to the most efficient modes ("avoid/shift")
- improving the energy efficiency of vehicles
- reducing the carbon intensity of fuels.

The policies included in Table 5.2 encompass instruments that alter the cost of transport across vehicles and modes, as well as regulatory measures limiting the scope for some of the mobility options. The table characterises the current level of stringency for each policy category across broad regions. This is a simplified and qualitative representation of the more quantitative and granular baseline policy characterisation conducted to enable modelling policy responses across regions in each scenario.

16 A scenario contemplating higher penetrations of hydrogen in the fuel mix, following policy developments particularly favourable for hydrogen technologies, is discussed extensively in IEA (2015b).

17 For instance, such a gap occurs when vehicle buyers value only two to three years of future fuel savings, rather than savings over the whole vehicle lifetime.

Table 5.2 Key transport policies in countries and regions

		National / Supranational / Regional								Municipal / City			
		Fuel taxation											
		Gasoline	Diesel	Low-carbon fuels (mandates, carbon intensity regulations)	Vehicle taxation (registration and circulation taxes)	Differentiated vehicle taxation (feebates)	LDV efficiency (fuel economy) standards	Heavy-duty trucking efficiency standards	EV policies (mandates, targets, differentiated taxation)	Pricing policies (road and parking pricing, congestion charges)	Regulatory limitations (low-emission zones, access restrictions, parking restrictions, registration caps)	Compact city policy incentives	Investment in public transport, walking and cycling
Impacts	Avoid/shift	●	●		●					●	●	●	●
Impacts	Vehicle efficiency	●	●		●	●	●	●	●	●	●	●	●
Impacts	Low-carbon fuels	●	●	●		●	●		●				
Canada		⇨	⇨	◑	◔		◔	◕	○	○	○	◔	◔
Mexico		⬂	⇩	◔	◔		●			○	○	○	◔
United States		⬂	⬂	◑	◔	○	●	◕	○	○	○	◔	○
European Union		⇧	⇧	◑	◑	●	●		●	◔	◑	◕	◕
Nordic Europe		⇧	⇧	◑	●	●	●		◑	◕	●	●	◕
Australia		⬀	⇨		◔				○	○	○	◔	○
Japan		⇧	⬀	◑	◑	●	●	◑	◑	◔	◔	◕	●
Korea		⬀	⬀		◔		◑		○	◔	◔	◕	●
Russia		⬂	⇩		◔					○	○	◔	◔
European TE		⇨	⇨		◔					○	○	◔	◔
Asian TE		⇩	⇩		◔					○	○	○	○
China		⇨	⬂	◑	◑	◑	◑	●	◑	◔	◑	◑	◕
ASEAN		⬂	⇩	◑	◑					◔	◔	○	◔
India		⇨	⇩	◑	◔		◔		○	○	○	◔	◑
Other Asia		⬂	⬂	○	◔				○	○	○	◔	◔
Middle East		⇩	⇩		○					○	○	○	○
Brazil		⇧	⇨	◑	◑	◑	◕			○	○	◔	◑
Other Latin America		⇩	⇩	◑	◔					○	○	○	◑
South Africa		⇨	⇨	◔	◔					○	○	◔	◔
Other Africa		⇩	⇩	○	◔					○	○	○	○

Taxation: ⇧ High ⬀ Medium/High ⇨ Medium ⬂ Low ⇩ Subsidy

Policy strength: No policy (blank) ○ Weak ◔ Weak/Fair ◑ Fair ◕ Strong ● Very strong

Notes: Fuel economy standards exist in Saudi Arabia alone among Middle Eastern nations. Although Australia has not adopted mandatory fuel efficiency standards, a fuel efficiency labelling programme, together with voluntary CO_2 reduction commitments from industry, have improved vehicle fuel economy. Nordic Europe is Denmark, Finland, Sweden, Iceland and Norway. TE stands for transition economies.

This section examines the policies outlined in Table 5.2, beginning with local policies (metropolitan/city-level) before discussing the national policies that lay the essential foundation for local policy action. More detailed information is then provided on the policy deployment compatible with each scenario. Both local and national instruments are indispensable to improve the sustainability of urban transport and reduce emissions in line with the 2DS.

Local policies

City-level policies that encourage people to use personal vehicles less – by avoiding or shortening trips, or by shifting to other modes of transport – are often termed travel demand management (TDM) policies. They can be broken into three categories: pricing, regulatory instruments, and support for public transport and non-motorised mobility (Table 5.3).

Table 5.3 Transport policies implemented in cities

Pricing	Regulatory instruments	Public transport and walking and cycling support
Congestion charging, cordon pricing, tolls (e.g. London, Milan, Singapore, Stockholm).	Access restrictions (e.g. "yellow label" restrictions in Chinese cities).	Shared bicycle systems and bicycle parking (e.g. *Vélib*' in Paris, Citi Bike in New York).
Parking pricing (widespread in North American, European and Japanese cities, most prevalent in the central business districts of densely populated cities).	Low-emission zones (e.g. time-of-day restricted access for freight trucks, as in many European cities).	Investments in cycling and walking paths, and sidewalks.
	Registration caps (e.g. in Singapore, Shanghai and other Chinese cities).	Transit infrastructure projects/ extensions (e.g. the Paris *Métro*; Bogotá's *Transmilenio*).
	Parking restrictions/reductions in parking supply (e.g. progressive elimination of off-street parking in Copenhagen, Paris and other European cities).	Transit fare subsidies (e.g. local, regional and federal subsidies pay for roughly half of fares on systems in many European and Chinese cities).

Pricing policies that make driving more expensive than other transport options include congestion charging, tolls on specific sections of the road network and dynamic parking prices. These not only raise prices for drivers entering cities, but also make cars less convenient than other ways of accessing and navigating metropolitan spaces.

Regulatory limitations reduce the attractiveness of personal vehicles by restricting their use at certain times of the day or in specific urban areas, providing an incentive to rely on public transport services. Regulations can also give vehicles with reduced or no tailpipe emissions preferred or even exclusive access to certain roads and motorways.

Support for public transport and non-motorised mobility (walking and cycling) generally comes in the form of investments for the development of the public transport network or subsidies for the operation of public transport systems. These instruments aim to increase quality of service or lower costs for users. Public transport support makes sense only in the presence of sufficient potential for passenger uptake. Both the supply and use of public transport are far more viable in urban areas with high densities, and are well-coupled with policies promoting densification (Box 5.3).

Pricing policies

Only a handful of cities apply congestion charging and cordon pricing to manage transport demand, primarily in Europe (London, Milan, Stockholm and several cities in Norway) and Asia (Singapore). San Francisco's dynamic parking pricing programme, SFpark, acts as a sort of congestion pricing, extracting public revenue from parked rather than moving cars, adjusting parking prices at different times of the day and in different urban areas (Verhoef, Nijkamp and Rietveld, 1995).

Box 5.3 Compact city policies underpin sustainable urban transport

Policies that promote compact cities (OECD, 2012) are the first prerequisite for sustainable transport systems, because a sufficiently dense population is required for high-capacity public transport to be viable. Such policies are especially relevant in emerging and rapidly growing cities in developing countries, and in cities in the developed world with significant urban sprawl.

Greater density reduces trip distances. Well-designed, dense cities also enhance the viability of pedestrian-oriented streetscapes: small blocks with mixed-use buildings (e.g. businesses on the ground floor and residences above them) and a well-connected street grid. Measures promoting densification and those aiming to manage transport demand, both for passenger and freight transport, are likely to benefit each other. Polycentric cities with mixed-use developments also favour walking and biking, prerequisites for the successful deployment of public transport.

Compact city policies also need to integrate land use and transport planning in order to promote public-transport oriented development, mixed land use, and a pedestrian- and cycling-friendly urban environment. Densely populated European and Asian cities generally have stronger incentives to integrate urban and transport planning. Many cities in rapidly developing Asian economies, especially those with high urban densities, still lack adequate financing for public transport walking and biking. Such cities should make it a high priority to integrate land-use and transport projects, ensure that laws and zoning do not favour car use, and adopt best practices from other cities. Lower GHG emissions and reduced local air pollution would be the primary benefits.

Some densely populated metropolises in the emerging and developing world have already laid a strong foundation for alternatives to the car. For instance, integrated urban and land transport planning has enabled the evolution of urban mobility strategies in Latin America, the region that has led the way in deploying advanced bus rapid transit (BRT) systems.

To reduce dependence on cars, sprawling cities in developed nations need to deploy policies that encourage reuse of industrial land ("brownfield" developments), urban revitalisation, and densification including public-transport oriented development (ITDP, 2014).

Although road pricing and congestion charging are deployed in only a few cities today, analyses show that these measures are powerful ways of nudging travellers towards behaviours with fewer detrimental social and environmental impacts (Azari et al., 2013; Basso et al., 2011; de Palma and Lindsey, 2011). The power of pricing, together with the potential to calibrate price signals to local conditions, explains why such policies feature prominently in the 2DS.

Regulatory policies

Regulatory policies such as parking supply reductions have been adopted primarily by densely populated cities, mostly in Europe and Asia, but also in North America. Access restrictions targeting reductions in congestion and exposure to local air pollution (e.g. low-emission zones reserved for specific vehicle categories at certain times of the day) are common in several European countries (Sadler Consultants, 2015). In China, regulatory limitations even include vehicle registration caps; nearly 12% of China's urban residents live in six cities with strict vehicle registration caps.

Regulations that limit access to vehicles with low tailpipe emissions (highly fuel-efficient cars and hybrids) or none at all (electric vehicles) have been widely adopted in European cities (ISIS and PWC, 2010) and provide a potentially valuable incentive for consumers to buy such vehicles. These policies are adopted in the 2DS due to their capacity to reduce reliance on personal vehicles for urban passenger transport and to increase market uptake of fuel-efficient vehicles, spurring the transition to low-carbon transport fuels.

Investment in public transport and non-motorised mobility

High urban density is one prerequisite for sustainable urban transport, but it is not enough on its own. Funding of public transport is also vital. This funding can be broadly split into investments in infrastructure and subsidies for operations. Infrastructure investments are needed initially to establish networks suitable to the specific city form; in general, buses, tramways (light rail) and high-capacity systems – including bus rapid transit (BRT) and metros or urban rail – become appropriate in that sequence as population density and city size increase.

Although public transport projects are implemented at the city level, investments are often obtained from several levels of government (e.g. federal, regional and municipal), and sometimes leverage private funding, for example via public-private partnerships. Public and private investment in public transport infrastructure and operations varies considerably from region to region, as noted in the final column of Table 5.2.[18]

Investments and subsidies are necessary to bridge the gap between what can be recovered through fares and what is necessary to accelerate the uptake of public transport. The size of that gap is indicated by the farebox recovery ratio – the fraction of a public transport operator's operating expenses that are funded by passenger fares. The best performers in terms of capacity to recover costs are cities with higher shares of trips on public transport modes (UITP, 2002). In several European cities, farebox revenues contribute to around half of the operational expenses of public transport operators (Reynolds-Feighan, Durkan and Durkan, 2000; EMTA, 2010).

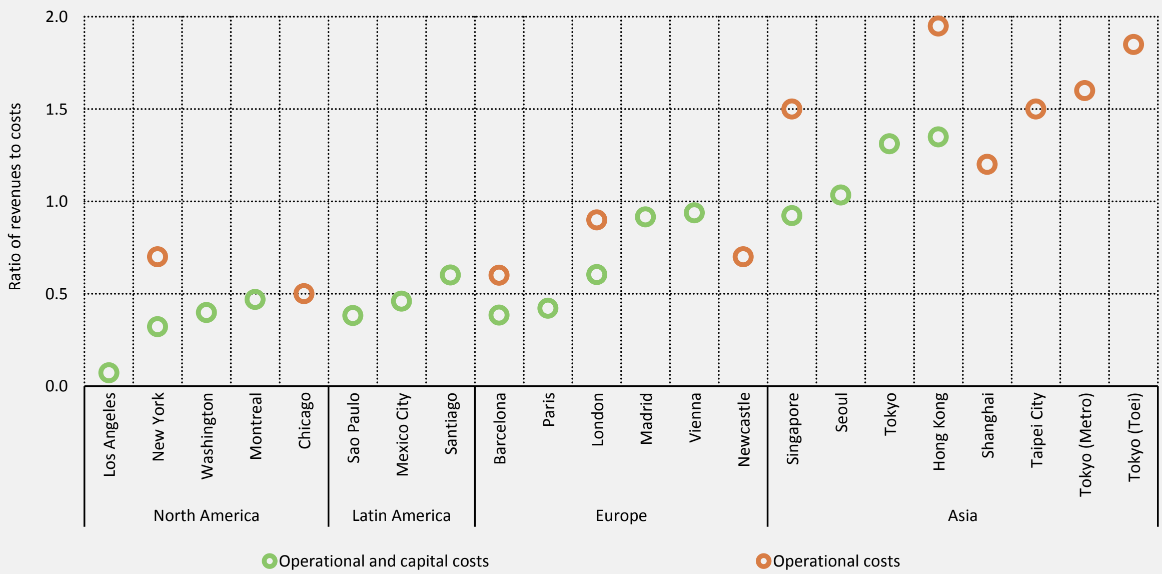
Farebox recovery ratios tend to be lower than the European values in low-density cities with high trip shares of cars (e.g. Houston, Texas), and far higher in Asian cities with high shares of trips on well-developed public transport networks and high urban densities, such as the cities of Hong Kong, Shanghai, Singapore, Taipei City and Tokyo (LTA, 2011; TLS, 2015) (Figure 5.15). In certain highly dense (mostly Asian) cities with limited suburbs, farebox recovery ratios may exceed 1; in such instances, public transport systems are financially self-sustaining, and additional revenues may be reinvested into system expansion or renewal projects, increasing comfort or reliability, or providing additional services.

Investments for network development are fully justified by the corresponding reduction in spending on the road network to accommodate more personal vehicles. They can also enable "value capture" – taking advantage of the increased land value that occurs in proximity to main transport nodes and boarding stations (Box 5.4). Subsidies for operations can be justified by direct social and environmental benefits, such as reduced congestion and air pollution, as well as higher productivity and improved road safety.

Investments in infrastructure and urban design that make walking and cycling safe, comfortable and convenient are a crucial prerequisite to attracting public transport passengers by making it easy for them to get to stations (Calthorpe, 2010). In many rapidly developing cities, in particular, use of public transport has been constrained by a lack of such urban landscapes. Such cities must urgently integrate sidewalks and bicycle paths into their development plans. In cities that have already been built, conversion of off-street parking into separated bicycle lanes is a proven strategy for shifting people away from cars.

18 This characterisation is primarily based on information on the extension per unit of urban land area of public transport networks in each region, an evaluation using GIS analysis coupled with data from the Institute for Transport and Development Policy Rapid Transit Database (ITDP, 2014).

Figure 5.15 Farebox recovery ratios in cities, grouped by region



Note: The reference to Tokyo refers to the entire metropolitan region, while Tokyo (*Metro*) and Tokyo (*Toei*) refer to the two rapid transit systems serving the Tokyo metropolitan region.
Sources: LTA (2011), "Comparison of public transport operations", www.lta.gov.sg/ltaacademy/doc/J11Nov-p71ComparisonofPublicTransportRevised.pdf (costs include only operational costs); TLS (2015), "Transit Leadership Summit, 2012-2014", http://transitleadership.org/docs/Transit-Leadership-Summit-2012-2014.pdf (costs include both operational and capital costs).

Key point *The ratio of revenues to costs tends to be high in densely populated Asian cities, lower in European and Latin American cities, and lowest in low density metropolitan areas of North America. This suggests that density is one of the determinants of the financial viability of public transport.*

Innovative business models, such as shared taxis and car-sharing and dynamic ride-sharing programmes, also stand to integrate more effectively in urban environments that favour public transport and reduced personal vehicle use. However, it is not clear what the impacts of such new mobility services and technologies will be on energy use, emissions and travel behaviour (Box 5.5).

National policies

National policies provide the indispensable framework needed to alter incentives and thereby modify transport behaviour. Only with these policies in place can local policy instruments provide a diversity of transport options. As well as describing effective national policies, this section briefly discusses policies that aim to reduce the costs of innovative technologies and mobility solutions that have not yet reached widespread commercialisation (not included in Table 5.2). The policies include "technology push" instruments such as public procurement framework legislation and direct funding for RD&D.

Fuel taxes

Fuel tax regimes increase vehicle operation costs and hence can influence the evolution of energy demand and GHG emissions in transport.[19] Fuel price interventions range from subsidies in most Middle Eastern and many Latin American countries to high taxes across European and some Asian regions, both on gasoline and diesel fuels (Table 5.2).

19 Fuel tax data are extracted from two sources: IEA statistics on energy prices and taxes, and international fuel prices and taxes published on a regular basis by GIZ (2014).

Box 5.4 Investments in public transport: Examples of value capture

"Value capture" refers to the possibility of supporting the development of public transport networks by tapping into the increase in land value around nodes and stations. Value capture tools can be grouped into three categories (OECD, 2000):

- allowing a single actor to develop both low-profit infrastructure projects and adjacent high-profit commercial projects such as retail stores, restaurants and hotels
- covering some of the costs of developing the public transport infrastructure or of land acquisition for network development through fees paid by the developers of adjacent commercial projects
- using property taxes, e.g. tax increment financing (widely used in the United States) to repay bonds issued to finance public transport development projects.

The Mass Transit Railway (MTR) Corporation in Hong Kong, China, offers a concrete example of successful public transport financing through value capture (Padukone, 2013). The MTR signs contracts with businesses operating along transport corridors that either give the MTR partial ownership; apportion to the MTR a fraction of property development fees; or redirect a fraction of the profits generated by those businesses to the MTR.

This programme, together with the constrained geography of the city (which keeps population density high) has helped the MTR to achieve the world's highest farebox recovery ratio: 185%. This gives the MTR ample capital with which to build and improve infrastructure, as well as to lower fares and attract more passengers.

Thanks in part to the MTR, personal vehicle ownership is far lower than in any comparably rich city (except Singapore), and public transport, walking and cycling have a far higher share of transport activity.

Box 5.5 New mobility: A paradise or a Pandora's box for energy and emissions?

Digital technologies may enable new business models and novel mobility concepts to emerge, but without large-scale, time-tested and empirical data, it is difficult to estimate the potential impact of these concepts – including real-time ride-sharing services such as BlaBlaCar; local demonstrations of automated driving by Google and Tesla; and municipal experimentation with Mobility as a Service (MaaS) (Smithsonian, 2014).

These technologies and business models could lead to incremental or even radical changes to transport systems, but some may under certain circumstances potentially increase rather than decrease energy use and emissions (Firnkorn and Müller, 2015; ITF, 2015).

Shared mobility, autonomous driving and MaaS models could integrate effectively with public transport services, easing the "first and last mile" connections of a trip and reducing car ownership. Shared mobility also leads to a better utilisation of vehicles throughout the day, which increases the relevance of operational over capital costs, and therefore enhances the competitiveness of fuel-saving technologies.

On the other hand, shared vehicles with automated driving may provide incentives for longer and more frequent trips, due to increased comfort, including the opportunity to perform activities other than driving. This could lead to more driving and exacerbate traffic congestion, and could draw people away from shared transport such as buses and metros.

Policies are needed to ensure that new mobility patterns develop in a way that is not detrimental to, and ideally is supportive of, public transport. With careful consideration of energy, emissions and other impacts, new mobility concepts may make significant contributions to the evolution of sustainable urban transport.

The removal of fuel subsidies is one of the most important policy developments in both the 4DS and the 2DS. The 2DS also requires the deployment of carbon taxes on transport fuels starting in 2020 at USD 35 per tonne of CO_2 (tCO_2) (which equates to about USD 0.09 per litre [L] of automotive gasoline), and increasing linearly to USD 210/tCO_2 (USD 0.54/L) by 2050. As well as imposing a price on emissions, carbon taxes are needed to discourage vehicle owners from responding to improvements in average fuel economies by using more fuel, and to reduce personal vehicle travel demand. In many regions and countries, including Europe, Japan and Korea, current taxes exceed the level of recommended taxation, providing price signals that already effectively limit GHG emissions per kilometre, even if they have not been conceived for this purpose.

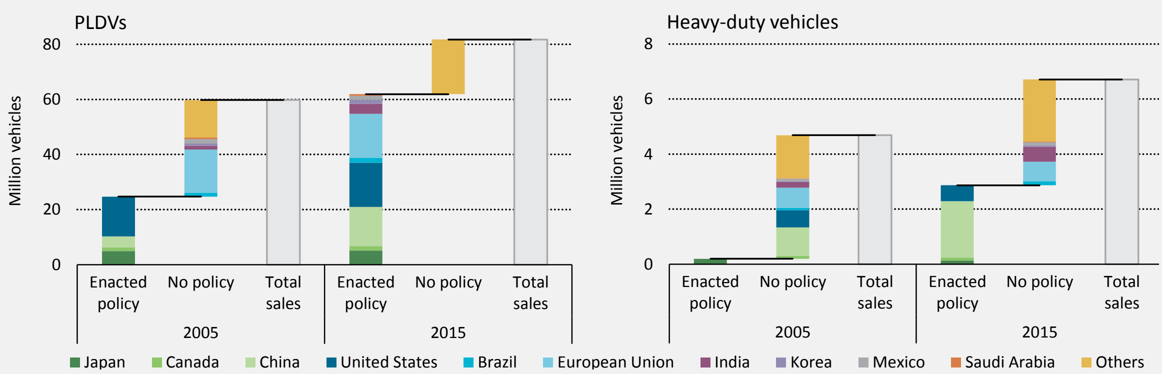
Fuel economy regulations

Fuel economy standards provide the indispensable foundation for important changes in consumer choices and business investment decisions. Meeting current fuel economy targets will enable the 4DS to be realised. Even tighter fuel economy standards are necessary to achieve the GHG emissions reduction targets in the 2DS.

Developed economies and regions with rapidly developing car markets have already introduced or are introducing fuel economy regulations. These regulations, sometimes accompanied by fiscal instruments, aim to promote the market uptake of vehicles with superior energy efficiency.

Today, roughly three-quarters of new car sales worldwide are subject to fuel economy regulations or fiscal policies (Figure 5.16) (Miller and Façanha, 2014). Fuel economy regulations exist in Canada, China, the European Union, India, Japan, Korea, Mexico, Saudi Arabia and the United States. Remarkable progress has been made recently in adopting fuel economy policies, especially in non-OECD economies: Brazil adopted fiscal policies incentivising the purchase of energy-efficient cars in 2012, while India and Saudi Arabia introduced fuel economy regulations in 2014.

Figure 5.16 New PLDV and heavy-duty vehicle registrations covered by fuel economy policies, 2005 and 2015



Note: China's Phase I fuel economy standards on passenger light-duty vehicles were phased in over 2005-2006, and went into force for new vehicle models in July 2005.
Source: IEA (2016), *Mobility Model*, January 2016 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Key point *The majority of new car sales are subject to fuel economy regulations. Despite substantial progress over the past decade, most trucks are still sold in markets without vehicle and engine efficiency standards.*

The effectiveness of increasingly stringent fuel economy regulations is demonstrated by the evolution of car fuel economy in the main global markets (GFEI, 2014). Improvement rates have been stronger in OECD countries, where fuel economy policies have been in force longer across more countries, than in non-OECD economies, where major progress has occurred only recently.

The fuel economy of LCVs is also regulated, but coverage is lower than in the case of cars. Currently, Canada, the European Union, Japan, Korea, Mexico, Saudi Arabia and the United States regulate the fuel economy of LCVs.

Regulations aiming to improve the fuel economy of trucks are also on the rise, with policy developments in the European Union, India, Korea and Mexico. At the moment, however, fuel economy standards for heavy-duty road vehicles have been implemented only in Canada, China, Japan and the United States. The share of MFTs and HFTs registered in countries regulating fuel economy is just over 40%.

For fuel economy regulations to be effective, it is vital to ensure that tested fuel economy matches on-road fuel economy as closely as possible. The gap between tested fuel economy and on-road fuel economy has grown substantially in recent years (Mock et al., 2014). This has been driven by changes in consumer behaviour (e.g. higher shares of vehicles with air-conditioning systems and higher frequency of use), by the increasing relevance of off-cycle energy consumption (e.g. for air conditioning) when the tested average fuel economy declines, and by manufacturers exploiting weaknesses in the test cycle to achieve better fuel economy ratings. Even larger differences between laboratory tests and on-road emissions of tailpipe pollutants have emerged from other studies (Franco et al., 2014), uncovering manipulations in vehicles undergoing tests from one manufacturer, Volkswagen (EPA, 2015a; VW, 2015a), and large discrepancies for some others. Volkswagen has also announced irregularities in CO_2 emissions testing (VW, 2015b).

All these issues call for regulatory actions ensuring that test cycles, despite being held under laboratory conditions, mimic real-life conditions as closely as possible. On-road tests of randomly selected vehicles can ensure on-road compliance.

To achieve the energy demand and GHG emissions reduction outlined in the 4DS and 2DS for the transport sector, policies need to be implemented that maintain the difference between tested values and on-road fuel consumption at less than 20%. A similar upper boundary should be set for the differences between tested and real-world emissions of local pollutants, to reduce the health costs and environmental impacts of transport systems.

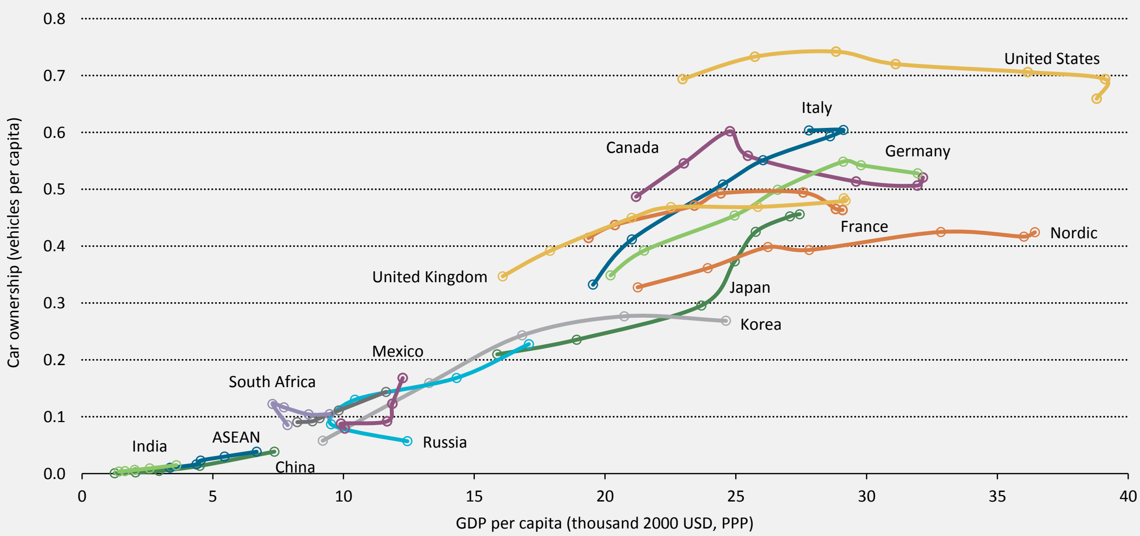
Vehicle taxes and feebates

Vehicle acquisition (or registration) and usage taxes alter the costs of buying and operating a vehicle. These instruments (grouped in Table 5.2 as vehicle taxes) apply to personal vehicles (2-wheelers and cars), where purchase prices affect consumers' evaluation of the total cost of ownership.

High taxation is applied to cars in Northern European countries (Denmark, Norway and Sweden); a diverse set of taxation policies exists across other countries in the European Union, and in Brazil, China and ASEAN countries; and weaker tax rates are applied in other regions, where there is little or no regulatory support for energy-efficient cars.

The percentage of households that cannot afford cars increases in countries with high vehicle taxes, lowering levels of vehicle ownership at a given income level (TIS, 2002) (Figure 5.17). This explains why increased vehicle registration and circulation taxes are among the most potent ways of reducing vehicle use in the 2DS, where 38% of urban passenger transport activity is avoided or shifted from cars to public transport compared with the 6DS.

Figure 5.17 **Car ownership rates as a function of GDP per capita in selected countries and regions, 1980-2010**



Note: Lines indicate the evolution of car ownership rates from 1980 to 2010 for countries with more than 0.07 vehicles per capita in 1980, and from 1990-2010 for all other countries.
Source: IEA (2016), *Mobility Model*, January 2016 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Key point *Car ownership tends to grow with increasing income levels (GDP per capita is used here as a proxy), reaching saturation for income levels exceeding USD 25 000 (2000 PPP) per capita. Saturation levels tend to be significantly lower in countries with high vehicle taxes, fuel taxes and population density.*

Tax exemptions, subsidies and "feebates" (a combination of fees and rebates) are typically applied to vehicle acquisition or registration taxes, but are also viable strategies for more finely calibrating circulation taxes according to vehicle efficiency. Differentiated vehicle taxation based on performance characteristics (mainly GHG and tailpipe emissions) complements other measures promoting energy efficiency in transport, such as fuel economy standards and labelling programmes providing information on fuel economy and emissions.

Brazil, China and several European countries have introduced fiscal measures favouring energy-efficient cars. Differentiated vehicle taxation is one of the pillars enabling the transformative changes in consumer choices required by the 2DS. It has been shown to stimulate significant market transformations in France (Klier and Linn, 2012), the Netherlands (Kok, 2013), Norway (Ciccone, 2014) and Sweden (Huse and Lucinda, 2014), and as such is being adopted elsewhere (e.g. in Israel [Udasin, 2014]).

Low-carbon fuels

Policies promoting low-carbon fuels have mostly taken the form of biofuel blending quotas and, more recently, regulations that tax or subsidise transport fuels based on their carbon intensity (i.e. well-to-wheel GHG emissions per unit of final energy supplied).

Blending quotas are enforced in Brazil, which has a unique profile of ethanol supply for transport purposes, and in the European Union and the United States, where supply quotas have been imposed to address energy security, rural economic development and climate change goals (Table 5.2). Other countries that enforce consumption quotas include Argentina, Canada, Colombia, China and several ASEAN countries, including Indonesia, Malaysia and the Philippines (IEA, 2015c). A similar subset of countries also applies tax credits on retail sales of ethanol and biodiesel. In Europe and the United States, mandates also include blending targets for advanced biofuels (which are designated as having lower well-to-wheel GHG emission intensities) (EC, 2015; EPA, 2015b).

Policies regulating the carbon intensity of fuels include the Low-Carbon Fuel Standard (LCFS) first implemented in California and subsequently in other US states and Canadian provinces, which aims to reduce the carbon intensity of transport fuels by 10% between 2010 and 2020 (CARB, 2015); the German Climate Protection Quota (IEA, 2015a); and the European Fuel Quality Directive (FQD), which requires a reduction in the GHG intensity of fuels by 6% by 2020 (EC, 2015). LCFS policies are similar and can be designed to be essentially equivalent to a well-to-wheel GHG fuel tax that becomes more stringent over time.

Growth in the advanced biofuel sector will depend heavily on policies that promote the construction and continued operation of commercial-scale plants producing low-carbon biofuels. Policies targeting the carbon content of fuels, such as the LCFS and the European FQD, are essential catalysts for the production of advanced low-carbon biofuels in the 2DS. They also broaden the scope of improvement beyond biofuels, favouring the deployment of innovative solutions in fuel production processes, promoting low-carbon electricity and hydrogen energy carriers. The LCFS is a good example of a policy framework that targets desired performance while remaining technology-neutral, avoiding the inefficiencies and dashed expectations associated with picking winners (Yeh and Sperling, 2010).

The efficacy of both these instruments – biofuel blending quotas and low-carbon fuel regulations – is likely to be stronger if they can reduce uncertainties about cost recovery over long periods, as investments in fuel production technologies need to be recovered over long time frames.

Other ‘market pull’ measures

National “market pull” measures are needed to support the deployment of fuel-efficient vehicles and technologies. These include targeted tax rebates and subsidies (already available in France, the Netherlands, Norway and Sweden) and zero-emission vehicle mandates (currently implemented in California). These policies have been complemented by local measures, such as congestion pricing exemptions for low-emission vehicles (e.g. in London and Milan) and other instruments favouring EVs, such as fee exemptions (e.g. for EVs on ferries in Norway) and access to bus lanes (in Norway for EVs). The effectiveness of these instruments is corroborated by rapid recent growth in EV markets in countries and regions that apply them, such as California, France, the Netherlands, Norway and Sweden.

Market measures that better reflect the social and environmental costs of driving are also an effective means of reducing travel in personal cars and shifting it to other modes (Hensher and Puckett, 2007; Börjesson et al., 2015). Pay-as-you-drive insurance programmes typically reduce adopters’ annual driving distances. Congestion charging or distance-based charges also shift taxes from vehicle ownership to vehicle usage, and so better reflect actual social and environmental costs.

In certain cities (such as China’s megacities and Singapore) and across regions with aggressive local air pollution and efficiency targets (such as California), policies designed to take old and polluting vehicles out of operation – which may include incentives to buy more efficient vehicles – may be needed to address severe air quality concerns and accelerate uptake of new technologies.

Technology push

"Technology push" policies, such as public procurement framework legislation and direct RD&D support, complement "market pull" and regulatory measures to help innovations bridge the difficult transition to commercial diffusion. Key areas of relevance for RD&D support are vehicle efficiency and fuel switching (e.g. to develop advanced biofuels). One of the best global examples is the Vehicles Technologies Office of the United States Department of Energy (US DOE), which provides RD&D support for EV technologies, advanced combustion engines, lightweight materials and alternative fuels, with a budget close to USD 1 billion between 2014 and 2016 (US DOE, 2015). A similar task is performed by the European Green Vehicles Initiative, established under the European framework programme for research and innovation Horizon 2020 with a budget of EUR 3 billion from 2014 to 2020 (EGVI, 2013).

Direct RD&D support for the development of PHEVs has reduced battery costs and increased energy density (Howell, 2014). Its role is crucial to maintain momentum for these developments. In the case of fuels, Israel's Fuel Choices Initiative provides domestic support for research into oil alternatives and advanced mobility (FCI, 2015).

Finally, large, co-ordinated and well-planned infrastructure investments will be needed to shift passenger transport to high-speed rail and to shift freight to more efficient rail and marine transport.

Policy formulation

Policies at all administrative levels need to be grounded on the analysis of all costs and benefits they generate. To be credible, effective and sustainable, policies need to integrate solutions providing the highest benefits at the lowest marginal costs, progressively moving towards options delivering lower ones. Technology deployment accounts for the market penetration of technologies with progressively increasing incremental costs of energy efficiency improvements. The lowest cost improvements are realised for ICEs, then hybrids, and then electrified powertrains using low-carbon electricity. Policies must not only strike a balance among several goals (e.g. abating local pollutants as well as GHG emissions, reducing congestion, public health, safety, access and equity), but also account for differing cultural, institutional and political contexts.

To ensure that taxation policies are effective, credible and durable, transparency of revenue streams is essential. Unless the benefits are clearly and convincingly demonstrated to the affected public, new taxes are unlikely to be viable in the long term. Revenue-neutral taxes, where funds collected are redistributed (e.g. to vulnerable or most affected demographics, or to support more sustainable transport, such as public transport, walking, cycling or EVs) are the most interesting option for governments not seeking new revenue streams. Allocating funds directly to public transport and alternative mobility has the advantage of communicating coherence in the public policy agenda. Some of the fiscal policies recommended here for the 2DS can increase public revenues, providing a way of complementing revenue losses due to the declining importance of fossil fuels.

Policy deployment consistent with the 2DS

National policies

At the national level, two fiscal instruments and one regulatory policy enable the 2DS to be realised. The first fiscal instrument is **fuel taxes that incorporate the costs of GHG emissions**. In the 2DS, national fuel taxation regimes gradually move towards carbon taxes, which tax transport fuels according to their well-to-wheel GHG emissions, plus a constant tax to cover road infrastructure construction and maintenance. Carbon taxes begin in 2020 at USD 35/tCO_2, and increase linearly to USD 210/tCO_2 by 2050. In countries where the current level of taxation is greater than the taxes implied by this schedule, fuel taxes are maintained at current levels until the carbon tax schedule catches up with them.

Vehicle taxation is the second fiscal policy needed to keep transport emissions on a 2DS trajectory. By mid-century, most countries and regions – including OECD countries in Europe and America, Japan, ASEAN member countries and China – have vehicle purchase and circulation taxes at levels 60% to 80% of the current high taxes in the Nordic countries, which have lowered rates of vehicle ownership. The increase in vehicle taxes occurs more slowly in OECD non-member economies.

Another fundamental development needed in the 2DS is regulatory: **fuel economy standards** for LDVs and trucks need to be broadened and tightened beyond current regional coverage and timelines, and combined with **differentiated taxes based on vehicle efficiency**.

- For cars, fuel economy standards and differentiated vehicle taxation (both of which foster the deployment of fuel efficient vehicle technologies) lead to a reduction of average on-road fleet-wide fuel economy from 9.5 litres of gasoline equivalent (lge) per 100 km in 2015 to 6.4 lge/100 km in 2030 and 4.0 lge/100 km by 2050. This is consistent with the target set by the Global Fuel Economy Initiative to halve the fuel consumption per kilometre of new PLDVs by 2030 (GFEI, 2011).
- In the 2DS, fuel economy standards are also deployed for heavy-duty road vehicles. By 2050, the specific energy consumption of the truck fleet is 23% lower than in 2015. Fuel consumption improvements in MFTs and HFTs of 30% and 25%, respectively, are partly offset by faster growth of the heavy-duty vehicle stock.

Fuel economy standards, differentiated vehicle taxation and policies increasing the utility and market penetration of EVs – along with significant reductions in battery costs – enable **increased electrification of vehicles**. The degree of electrification envisaged in the 2DS is aligned with the targets announced by several governments in the OECD and in rapidly developing OECD non-members. At 18.4 million LDVs, it nearly meets the ambitious goal of the Electric Vehicle Initiative to deploy 20 million EVs by 2020 (CEM, 2015). It is also consistent with the Paris Declaration on Electro-Mobility and Climate Change, announced at the 2015 Conference of the Parties to the United Nations Framework Convention on Climate Change (COP21). The declaration targets more than 400 million electric 2-wheelers (up from more than 200 million today, nearly all in China) and more than 100 million EVs (up from 1 million today) by 2030. In the 2DS, the share of electric 2-wheelers grows to 41% and the share of electric passenger cars to just under 9% by 2030. Achieving these levels of deployment of advanced vehicle technologies is unlikely to be feasible without substantial RD&D support to achieve cost reductions.

Local policies

Achieving the ambitious 2DS targets will require an increasing number of large cities to adopt an aggressive portfolio of policies that mitigate the local social impacts of personal vehicles while providing a range of passenger transport options. Actions are necessary first in large cities because of their greater potential for change, made possible by economies of scale.

City-level measures fall into four broad categories:

- pricing measures
- regulatory restrictions on the operation and access of vehicles (designed to favour vehicles with greater efficiency and fewer emissions)
- investments in public transport, and walking and cycling
- measures favouring the deployment of infrastructure to accelerate the uptake of alternative fuels.

From an operational and political perspective, certain policies are best phased in gradually. In particular, public transport infrastructure investments should be designed to meet existing needs, and so should be carried out only after thorough research has demonstrated a concrete need for new capacity, and in tandem with compact city policy deployment. Operational subsidies for public transport could be phased in gradually, according to budgetary constraints. In low-density cities, they are unlikely to be as effective as in high-density cities.

Pricing policies such as congestion charging and road tolls also benefit from incremental introduction, expansion and price hikes as strategies to test and learn, to prevent public backlash, and to slowly accumulate revenues. It is crucial for both the credibility and the sustainability of the measures that all revenues generated are transparently allocated in the public interest, preferably to promote alternative mobility options, e.g. to subsidise public transport fares or fund transit infrastructure upgrades or extensions.

Policy intensity can vary so local policy makers can tailor measures to local needs and context. Two stylised extremes are presented below: an aggressive approach wherein major cities bear the main responsibility for shifting mobility patterns, and a broad effort across many smaller cities. In reality, effective global implementation of local policies is likely to consist of a mix of both cases.

Under the aggressive policy approach, 25% of all cities above 500 000 inhabitants manage higher or variable prices for off-street parking (or other congestion charging programmes) in central business districts and other congested urban areas, as well as restrictions on polluting vehicles under certain conditions (e.g. time of day or level of congestion/pollution). These cities need to put in place or toughen one or two new policy measures each decade.

Sprawling cities with widely dispersed suburbs and exurbs (such as Houston and Los Angeles) need to encourage urban densification and polycentric, public-transport oriented development. This should be complemented by pricing programmes like San Francisco's dynamic parking pricing, and restriction of parking in higher-density areas. Revenues from such programmes should support city bus systems connected with park-and-ride facilities outside the higher-density areas. Once sufficient alternatives to personal cars are in place, national and local pricing signals should be ratcheted up to the next level. Redistribution of revenues to low-income and rural populations can ensure that equity impacts are properly addressed.

High-density cities in developing and emerging economies should give priority to investments in high-quality public transport infrastructure and in walking and cycling infrastructure to facilitate access to stations. This should be primarily targeted at districts with the greatest demand to provide a high-quality and reliable service that will create a loyal customer base. Value capture financing (Box 5.5) is recommended as a means of raising the capital needed for such projects. As they disproportionately impact personal car owners, vehicle and fuel taxes mostly target higher-income socio-economic segments and are therefore viable ways to generate revenues. Nevertheless, care must be taken to redistribute revenues to soften the impact on affected groups such as taxi drivers and rural produce vendors delivering to urban markets.

A broad policy approach to urban transport can also achieve the 2DS targets by requiring a greater number of cities (75% of all cities with more than 500 000 residents by 2050) to roll out a more modest but still comprehensive and co-ordinated portfolio of policies. In this case, cities would need to implement and gradually increase the scope and stringency of at least three policies across different categories (price, regulatory and public investment measures), rather than aggressively implement and gradually ramp up a majority of the measures shown in Table 5.3. As much as they can, small cities (150 000 to 500 000 people) need to support the efforts of large, dense cities by promoting public-transport oriented development and TDM policies, by strengthening public transport, and by ensuring that urban form develops in a way that minimises personal vehicle travel.[20]

Recommended actions for the near term

To meet the 2DS goals, policies are required that affect all transport modes across all regions. The following actions – including complementary measures undertaken at different administrative levels – are critical to transforming urban transport systems in order to meet these goals and must be given priority over the coming decade (see Chapter 1 for policy recommendations on intercity and long-distance transport):

- Remove fuel subsidies and introduce CO_2 or fuel taxation based on well-to-wheel GHG emissions. Regions with low fuel taxation regimes need to act first.
- Introduce or toughen regulations on the fuel economy and pollutant emissions of light-duty road vehicles; widen their regional coverage; extend improvement targets for the 2015-30 period (especially in non-OECD economies); and ensure that the gap between tested fuel economy and on-road fuel consumption remains below 20%.[21]
- Widen the geographical deployment and extend to 2030 (or beyond) regulations on the carbon content of fuels, coupled with mandates on advanced biofuels or performance-based incentives for low-carbon fuels that are capable of stimulating investments.[22]
- Deploy progressively, starting in congested cities above 500 000 inhabitants and most urgently in megacities, measures that reduce congestion and local pollution and improve safety, including: **pricing policies** such as congestion charging, cordon pricing and dynamic parking pricing; **regulatory restrictions** on the operation and access of vehicles that favour vehicles with the highest energy efficiency and lowest pollutant emissions; and **investment in public transport** to develop networks and support operations.
- Prioritise policies that progressively increase the density of large sprawling cities, e.g. through brownfield transformation and public-transport oriented development, to increase the economically viable alternatives to personal motor vehicles.
- Invest in the long-term development of walking and cycling infrastructure and public transport networks in densely populated cities, prioritising corridors with the best prospects for frequent use.

20 Policy deployment scenarios consistent with the 4DS and 6DS are outlined in Annex F, available online at: www.iea.org/etp/etp2016/annexes.

21 In addition, the scope of fuel economy regulations must be broadened to include trucks, which must be preceded by benchmarking of truck operations and vehicle efficiency for different vehicle and mission categories in the main truck markets – see the transport section of "The Global Outlook" (Chapter 1).

22 Policies supporting biofuels are particularly important as biofuels seem to have the best prospects for substituting for fossil fuels in long-distance and heavy-duty applications, as well as in commercial aviation – see the transport section of "The Global Outlook" (Chapter 1).

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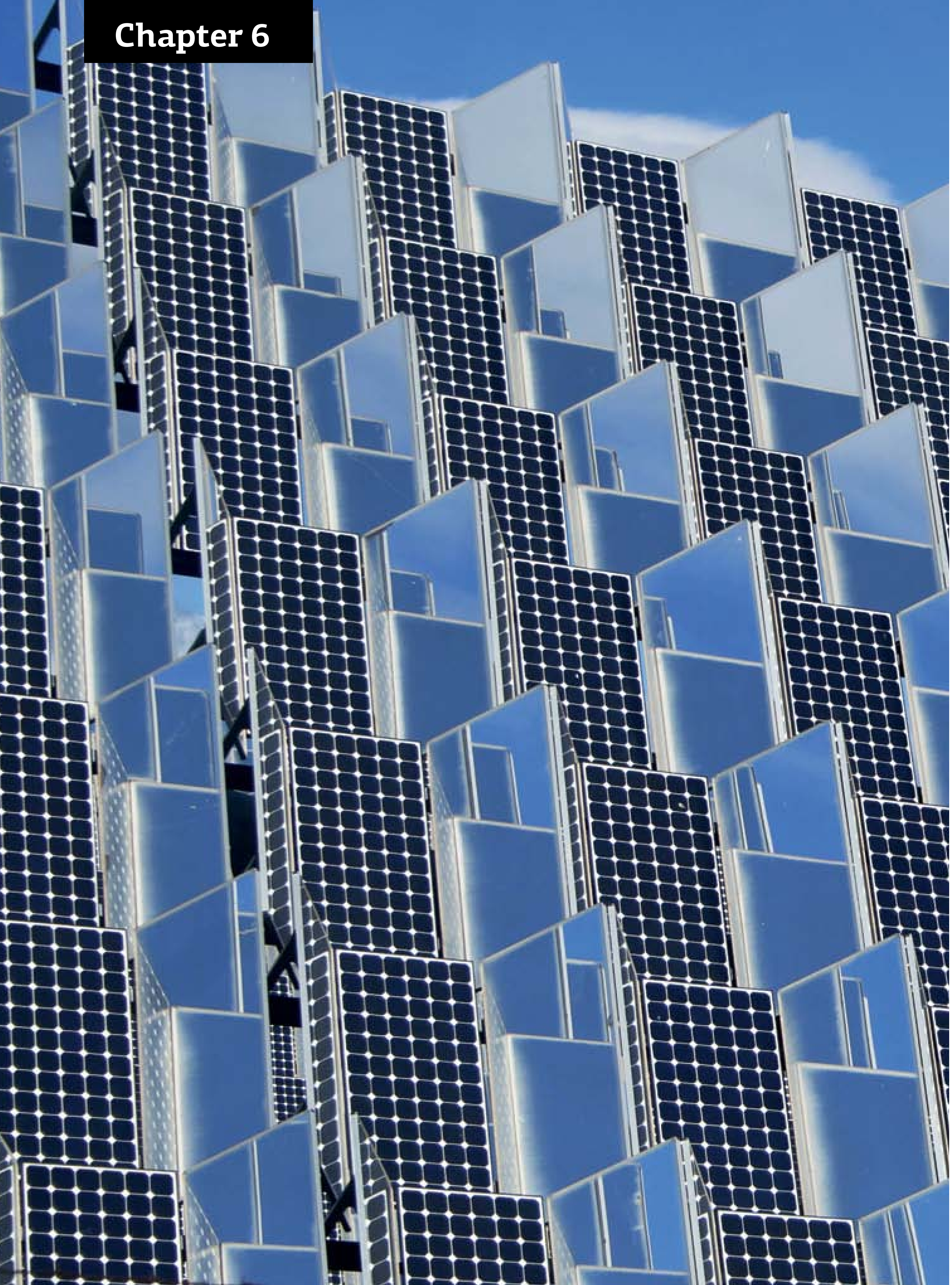
Chapter 6



Energy Supply in Cities

An increased access to and reliance on a clean energy supply is a prerequisite for greater sustainability in cities. Decentralised electricity and heat generation within or close to urban areas, as well as system integration among different energy grids, can play an important role in achieving a global transition to sustainable energy systems.

Key findings

- ***Local energy sources (e.g. solar thermal, excess heat from industrial facilities, municipal solid waste [MSW] and rooftop solar photovoltaics [RTSPV]) are cost-effective in many cases today compared to traditional supply options located outside cities*** *and can play a relevant role in meeting the future electricity, heating and cooling needs of cities.*
- ***Integrated urban energy infrastructure planning is necessary to realise the urban supply potential.*** *Smarter urban energy network design and operation can exploit the diversity of local energy sources within city confines, increase the hosting capacity for distributed energy resources, and unlock the potential to utilise locally generated excess heat or waste streams.*
- ***Electricity is a major energy carrier for cities, accounting for an estimated 22% of all final urban energy needs.*** *In the 2°C Scenario (2DS), by 2050 it becomes the largest final energy carrier in cities with a share of 33% (or an absolute demand of 25 800 terawatt hours [TWh]).*
- ***The technical potential of RTSPV is around 9 100 TWh, an amount corresponding to 30% of the electricity needed in cities in 2050 in the 2DS.*** *Taking into account competition with alternative generation options, almost 2 400 TWh or around 8% of urban electricity needs are covered by urban RTSPV in 2050 in the 2DS.*
- ***The technical potential electricity and heating supplies from MSW, wastewater and sewage gas are estimated to be around 1 000 TWh of electricity and 11 exajoules (EJ) of district heat by 2050.*** *Though not significant in absolute levels (e.g. equivalent to less than 4% of urban electricity needs in 2050 in the 2DS), these energy resources can provide relevant cost savings for many city services.*
- ***Cities and industrial users can benefit from industrial excess heat (IEH) deliveries under favourable local conditions, such as limited distance between production sites and end users, and continuous and compatible supply.*** *Globally, 2.7 EJ of IEH or 2% of industrial final energy use could be technically recovered.*
- ***Today's distribution grids could be changed into active distribution networks*** *by using distributed energy resources to resolve challenges in grid management, implementing advanced monitoring and control technologies for improved real-time management, and utilising demand response technologies for load control.*

Opportunities for policy action

- *Cost-effective supply strategies, suited to local and national needs, can be identified through integrated assessments, mapping of local energy resources and accurately estimating urban final energy demand. For example, strategic heating and cooling planning can help to identify cost-effective opportunities for excess heat recovery.*
- *Roofs remain an unused resource in cities. Solar maps can help homeowners understand the costs and benefits of installing RTSPV modules or solar thermal water heating panels, especially in small cities, which account for 40% of the global RTSPV potential.*
- *The integration of increasing shares of RTSPV can cause challenges for balancing electricity load. The concentration of energy service demands in cities offers part of the required flexibility (e.g. demand response from electric vehicles [EVs]), not only to the local electricity system but also to the national one. Cities should explore the potential of these flexibility services as local business opportunities.*
- *MSW and wastewater treatment, generally considered a burden for cities, may become additional revenue streams (e.g. from selling electricity, heat, fertilisers). Cities should develop waste and water management plans that include energy and material recovery options. Smaller cities can collaborately develop strategies and jointly operate a waste-to-energy (WTE) plant.*
- *For IEH recovery, promoting process integration techniques as part of energy management systems can more effectively identify energy efficiency opportunities, especially for the often site-specific low-temperature heat sources. Improved industrial process integration would then open opportunities for further sustainable benefits through exports to local thermal networks or IEH-based electricity generation.*
- *Policies can support the development of new business models to sustainably manage district energy networks by prioritising the use of low-carbon local energy sources, such as benefiting from the advantageous marginal carbon footprint of recovered excess heat.*
- *Collaborative public-private research and development efforts should target technologies needed in the urban context, such as improvements in thermal storage technologies for excess heat recovery.*
- *The benefits and costs of smarter urban energy infrastructure depend on the regulatory framework and incumbent investment conditions. These conditions vary greatly region to region. Equipping network owners and operators with modern planning tools, based on remote monitoring and control of energy infrastructure, can deliver significant cost and efficiency savings. Deployment of distributed generation (DG) can be accelerated and integrated at a lower cost if investments in increasing the observability of the network are facilitated early.*
- *Standardisation and interoperability of smart grid solutions are necessary to deliver the type of cross-optimisation solutions discussed in this chapter. Key areas to be addressed include interfaces between power systems and smart end-use equipment (heating systems, EVs, consumer-owned storage, smart appliances) and interoperability between energy networks.*

Cities are centres of energy consumption. As shown in Chapter 3, urban areas account for around two-thirds of global final energy use. Meeting these energy needs brings both challenges and opportunities. Cities may have added opportunities to provide more efficient services, such as more efficient public transport solutions,[1] but the options for energy supply sources within cities, while existing, are limited, requiring cities to rely on energy imports to meet their total energy needs.

Renewable energy sources within cities exist. Environmental or geothermal heat may be used for space and water heating in buildings (see Chapter 4), and the rooftop areas or facades of buildings can be used to produce electricity in solar PV systems or to warm water in solar thermal modules. But their potential is strongly influenced by urban form: factors such as the city's spatial structure, building types and population density determine which urban energy sources are available. Sprawled cities with low population densities have larger roof areas, thus allowing solar PV to meet a greater amount of local electricity needs than densely populated cities with high-rise buildings. Densely populated cities, due to the concentration of energy demand, may provide favourable economies of scale for more efficient and less carbon-intensive energy supply solutions that would not be viable in low-density cities. District heating and cooling (DHC) networks, requiring sufficiently high heat or cooling demand densities to be economic, are an example. Thus, while energy supply sources exist within cities, the options vary and cities must rely on energy imports to meet their total energy needs.

Energy imports such as electricity can come from distant centralised sources or more decentralised local sources on the city periphery. Centralised supply options such as large-scale power plants may provide benefits in term of economies of scale but may require transmission infrastructure. Options close to cities that use local fuel sources reduce the transmission needs, but may result in higher specific generation costs if plant sizes are smaller. Further, the choice between centralised or decentralised supply options may be influenced by considerations other than cost, such as resilience against supply disruptions. Opportunities for electricity generation in peri-urban areas are not discussed in this chapter, but an analysis of the electricity generation potentials from solar and wind energy close to cities can be found online.[2]

The first section of this chapter discusses the technical potential of urban energy sources. The focus is on energy supply sources for electricity generation and DHC, which are the two main areas where energy sources within cities can play a role.[3] The energy sources discussed include RTSPV, MSW, sewage sludge, and excess heat from wastewater and industrial processes.

The second section of the chapter presents an analysis of how urban electricity and heat needs are covered in the 2DS and quantifies some of the economic and security benefits of local supply options.

The third section examines the energy distribution infrastructure needed to transport energy within a city. Cities present unique circumstances involving high density of loads, variety and diversity of loads, and a breadth of distributed supply options. How urban infrastructure is designed, built and operated can yield vastly different outcomes for energy delivery. On the technology side, new developments in distributed energy resources are changing the technical and economic conditions of energy networks. Distributed PV, storage, electrification of heat and transport, and low-temperature district heating networks open up new challenges and opportunities at the local level.

1 See Chapter 5 ("Sustainable Urban Transport") and Chapter 4 ("Energy-Efficient Buildings in the Urban Environment") for more details on energy efficiency opportunities in cities.

2 See Annex J at www.iea.org/etp/annexes.

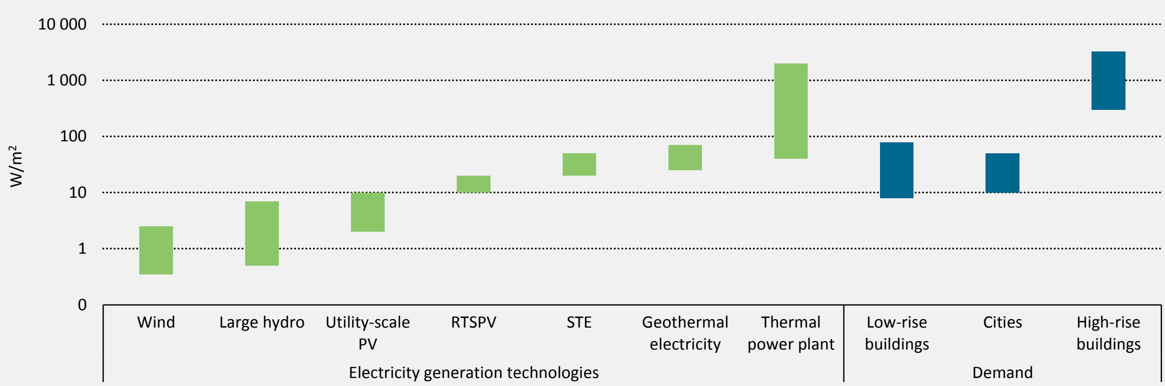
3 Significant resources for other forms of final energy, e.g. liquid or gaseous fuels, do not exist in cities. Hydrogen may become a relevant energy carrier in the future, but its production relies on other energy sources such as electricity or gas. The role of hydrogen for the transport sector is discussed in Chapter 5.

Energy supply options for cities

Cities account for an estimated 60% of global final energy demand, increasing slightly to 63% by 2050 in all *ETP* scenarios.[4] In absolute terms, however, the increase in final energy demand can be reduced from 175 EJ (62%) between 2013 and 2050 in the 6DS to 124 EJ (44%) in the 4DS and further down to 35 EJ (12%) in the 2DS. Still, despite efficiency improvements, cities will remain hubs of energy consumption, with an increasing share of global population living in urban areas.

Local energy sources within cities can help meet these energy needs. The available energy resources are, however, typically not sufficient to cover all energy needs, and self-sufficiency in low-carbon energy supply will not be an achievable goal for most cities.[5] This can be demonstrated by comparing the typical energy-demand densities of individual houses and high-rise buildings with the energy-supply densities of various renewable energy technologies or fuels (Figure 6.1). Only geothermal energy, solar thermal electricity (STE), RTSPV and use of MSW for thermal electricity generation have power densities matching the demand densities of 10-30 watts per square metre (W/m^2) observed in cities. Not shown in the graph are the absolute area requirements needed to meet a city's energy demand. Even if the supply densities are in a similar range to the observed demand densities, the areas available for energy technologies are limited, because land is a scarce commodity in most cities. Opportunities for local energy sources may exist outside but still close to cities in the so-called peri-urban areas. Due to the large availability of land there (e.g. for wind generation), the lower energy-demand density is a less constraining factor. The city of Copenhagen is an example, investing in 100 wind turbines (or 360 megawatts [MW]) in and outside its municipality as part of plans to become carbon-neutral by 2025 (City of Copenhagen, 2014).

Figure 6.1 **Energy supply densities compared with typical energy demand densities**



Note: m^2 = square metres. Figures and data that appear in this report can be downloaded from www.iea.org/etp2016.
Sources: McKay, D.J.C. (2013), *Solar energy in the context of energy use, energy transportation and energy storage*; Smil, Vaclav., *Power Density: A Key to Understanding Energy Sources and Uses*, Figure 7.3, p. 203, © 2015 Massachusetts Institute of Technology, by permission of The MIT Press.

Key point *Energy demand densities for cities constrain the provision of energy services through renewables within cities alone.*

4 See Chapter 3 for more information on the approach used to estimate the urban share in global final energy consumption.
5 There are examples of zero-carbon cities, such as Masdar City in the United Arab Emirates and Dongtan in China, but these cities often represent new urban areas, being developed on the planners' drawing boards to meet their ambitious targets.

Important exceptions to this low-density characteristic of local energy sources are MSW and environmental or geothermal heat, energy carriers characterised by high energy densities.[6] MSW can be used in WTE plants to produce electricity or district heat. In Denmark, almost 18% of the district heat supply in 2013 was generated from waste (DEA, 2015). The use of geothermal heat for district heating is more limited because it depends on the availability of hot thermal resources. Systems are operating in Iceland, Germany, France and Hungary. An extreme example is Reykjavik, Iceland, where 95% of the buildings are heated by geothermal energy.

The high demand densities in urban areas present the economies of scale needed for the infrastructure to recover and use excess heat, otherwise vented to the environment, for heating or cooling. Wastewater in cities can be a low-grade heat source (other examples for heat sources being metro systems and electricity substations), which after its temperature is raised in a heat pump, can be fed into district heating grids. The largest heat pump station in the world is operating in Helsinki for that purpose (Riipinen, 2013). Furthermore, excess heat from industrial production processes at medium to high temperature levels can be directly fed into a district heating network (or in combination with an absorption heat pump into district cooling grids), but uses in other industrial production processes or for electricity generation can be alternative options.

This section discusses the technical potential and options for energy sources within and close to cities to supply electricity and heat generation. For energy sources within cities, the analysis focuses on RTSPV, MSW as well as sewage gas, and low-temperature heat from wastewater treatment. The section is complemented by a discussion of the excess heat potential from industry.

The technical potential for electricity and district heat generation within cities as well as the technical potential for IEH are summarised in Figure 6.2. For electricity, RTSPV has the largest technical potential, while for heat, MSW leads. Globally, in 2050 in the 2DS, these technical potentials compare to a final demand of cities of 26 000 TWh for electricity and of 2 500 TWh for district heating. How much of these potentials can be realised depends on economic factors, further constraints on the demand site (e.g. spatial location of IEH sources to heat consumers in cities) and demand potential for district heating or cooling (e.g. depending on climate zone).

Energy sources within cities

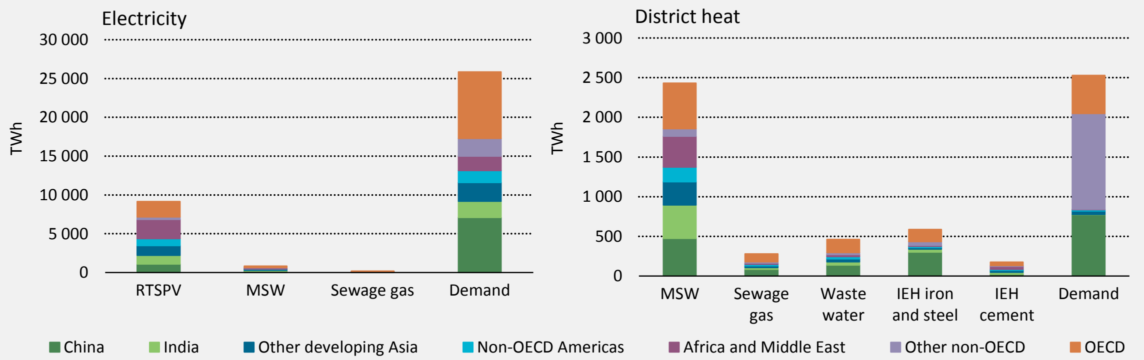
Solar rooftop PV potential in cities

Roofs of residential, commercial and industrial buildings in cities are often left unused, and can become a resource to convert the energy of the sun into electricity or thermal energy.[7] In 2014, almost 60% of the global solar PV capacity of 176 gigawatts (GW) was installed on buildings (IEA, 2015a). Comprehensive data on how much of the capacity was installed in urban areas do not exist. But data from some countries suggest that the deployment of RTSPV has been concentrated in less populated areas, as shown in Figure 6.3 for municipalities in the federal state of North Rhine-Westphalia in Germany. There, higher shares of rooftop PV in covering residential electricity go hand in hand with lower population density. In some rural communities, high levels of PV deployment result from rooftop PV systems on farm buildings.

6 Ground-source heat pumps for space heating are characterised by a heat density of 40-100 W/m², while the lower heating value (LHV) of MSW can be in the range of 8-16 megajoules per kilogramme (MJ/kg), depending on the waste composition (for comparison, diesel has an LHV of 46 MJ/kg).

7 Besides using roofs for solar energy, there is also increased interest in using the roof area for gardens or vegetation in general for various purposes (to absorb rainwater, to provide insulation or to mitigate the heat island effect of cities).

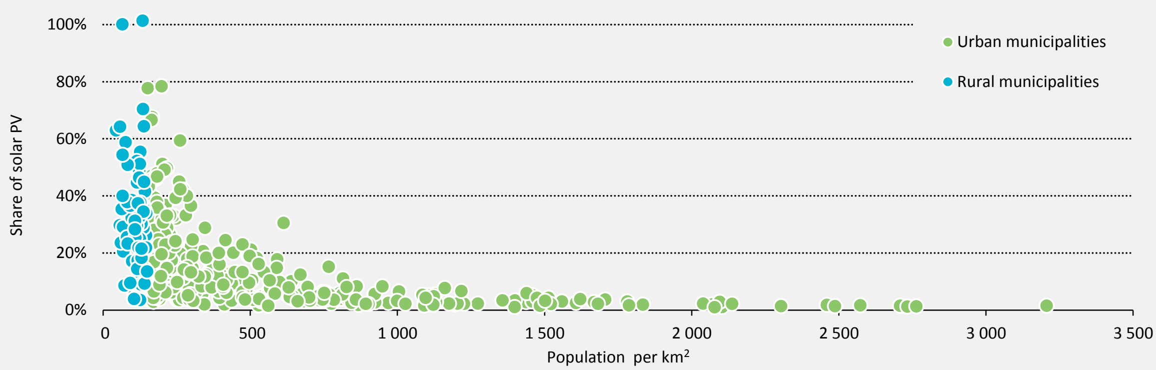
Figure 6.2 Technical potentials for electricity and district heat generation in cities in the 2DS



Notes: For MSW, electricity and heat potential are based on a co-generation plant with an electric efficiency of 19% and a heat efficiency of 79% in back pressure mode, i.e. at the point of maximum heat output (co-generation refers to the combined production of heat and power). For sewage gas, an electric efficiency of 22% and a heat efficiency of 48% have been assumed. Heat potential from wastewater based on an electric heat pump with a coefficient of performance of 4. Technical IEH recovery potentials refer to 2013 industrial stock.

Key point *Large technical potentials exist for electricity from RTSPV, while the technical potential for heat from MSW almost equals the demand in 2050 in the 2DS.*

Figure 6.3 Population density in North Rhine-Westphalia and share of solar PV in residential electricity consumption, 2011



Notes: km^2 = square kilometres. The definition of urban and rural municipalities follows the one used for Germany in the 2014 revision of *World Urbanization Prospects* (UN, 2014), i.e. communities with a population equal to or greater than 150 inhabitants per km^2 are considered urban. Shares above 100% indicate municipalities where solar PV generation exceeds the residential electricity demand.
Source: LANUV (2013), *Potenzialstudie Erneuerbare Energien NRW, Teil 2: Solarenergie* (Study of Renewable Energy Potentials NRW, Part 2: Solar Energy).

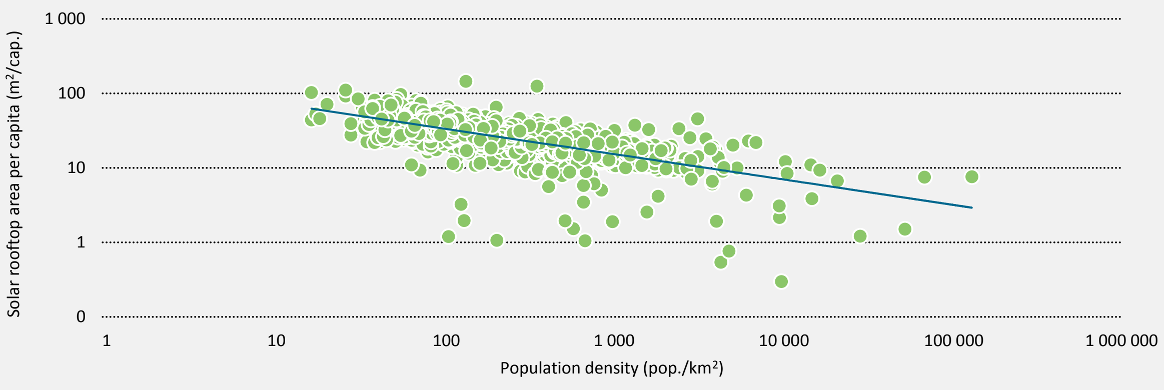
Key point *Urban form influences the availability and choice for solar PV, with larger contributions to electricity demand being observed in areas with lower population density.*

The correlation between density and the amount of demand met by PV illustrates that urban form is an important factor in constraining deployment of solar energy in cities. Urban form may affect technical aspects, such as less roof area per capita and more shading from surrounding buildings. Urban form can also influence solar deployment because of other, non-technical issues, such as building ownership. Agreement to invest in an RTSPV system may be more difficult to reach in multi-family buildings, which have several apartment owners, than in single-family homes. Urban form is an even more defining factor for urban energy consumption, resulting in a trade-off between energy efficiency and renewable potentials. Dense and compact urban areas can help to increase energy efficiency (e.g. better opportunities for public transport), but at the same time higher density often reduces the area on a per capita basis available for local renewable sources such as solar energy.

Cities have started to use solar maps to assess the potential of solar energy on their roofs. Examples include large cities such as New York and Paris as well as smaller ones such as Aargau in Switzerland (Mapdwell, 2015; Mairie de Paris, 2013; Meteotest, 2013). These solar maps provide building-specific information on the suitable rooftop area for solar energy and the expected annual solar PV generation (or solar thermal heat generation), sometimes combined with estimates for the costs of the PV (or solar thermal) systems.

Such assessments use geographic information system (GIS)-based methods, which apply three-dimensional models of buildings to determine the solar resource or shadow effects (Melius, Margolis and Ong, 2013). For estimating the RTSPV potential in cities on a global scale, such a GIS-based approach would be too elaborate. Here a different approach was chosen. From a data set of more than 1 500 cities, for which solar potential assessments were available, a correlation between suitable rooftop area per capita and population density was derived (Figure 6.4). This correlation was then used in the estimation of the urban rooftop potential for solar energy (Figure 6.5). It should be noted that this approach does not consider facade areas for building-integrated PV, which may lead to an underestimation of the PV potential in densely populated areas with high-rise buildings.

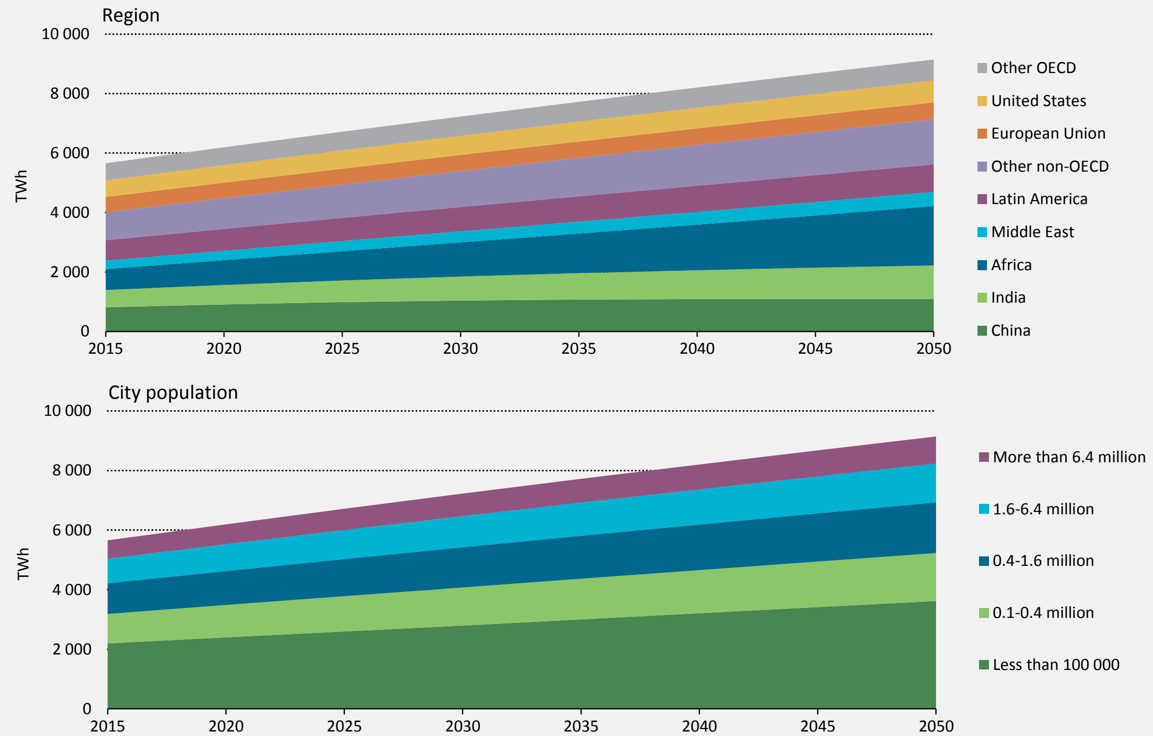
Figure 6.4 **Available solar rooftop area per capita in cities as a function of population density**



Note: m^2/cap. = square metres per capita; cap./km^2 = people per square kilometre.
Sources: List of data sources and more details on the estimation of the potential can be found in online Annex H at www.iea.org/etp/annexes.

Key point *Population density has a strong impact on the available rooftop area per capita for solar energy, ranging from 100 m^2/capita in less populated urban areas to 1 m^2/capita in high-density cities.*

Figure 6.5 **Technical potential for rooftop PV generation by region and city population**



Key point *Almost three-quarters of the technical potential for urban solar rooftop lies in cities outside the OECD; small cities with fewer than 100 000 inhabitants account for almost 40% of the potential.*

Globally, the technical potential of solar rooftop PV in cities is 9 100 TWh. This would meet 30% of the electricity needs of cities in 2050 in the 2DS, or almost 70% of the electricity demand of urban residential and commercial consumers. On a regional level, this share varies from 11% in China to 97% in Africa.

As shown in Figure 6.4, declining population density correlates with increasing rooftop area per capita suitable for solar PV. Since low-density cities are often also smaller in terms of total population, a large part of the technical potential (40%) for rooftop PV can be found in small cities with a population of fewer than 100 000 people (Figure 6.5). Large cities with a population of 1.6 million or more account for only a quarter of the potential solar rooftop generation in 2050. For buildings in rural areas, the rooftop PV potential has been estimated to be around 3 650 TWh in 2050, representing almost 10% of global electricity generation in 2050.[8,9]

8 The rural RTSPV potential is only a conservative estimate. Because no data on population density for rural towns were available, the average population density of the smallest urban city class with a population of fewer than 100 000 in a country was used for the rural population density. The actual population densities in rural areas are likely to be lower, resulting in a higher potential. See online Annex H at www.iea.org/etp/annexes for more details on the estimation.

9 The potential estimates are based on the assumption that all suitable rooftop area would be used for RTSPV. The roof area can, however, also be used for solar thermal water heating, which would result in a technical global potential of 36 000 TWh of heat from solar thermal collectors, if all urban roof areas were used for solar thermal water heating instead. This competition for roof area between RTSPV and solar thermal water heating is taken into account in the scenario analysis.

Given this correlation, policies for realising the RTSPV potential have to focus on small cities. These cities are often, however, least prepared for implementing RTSPV, due to lack of data, limited resources and expertise, and constrained governance capacities. Regional or national governments can play a critical role in closing these gaps. For example, the federal state of Baden-Württemberg in Germany developed an online available renewable energy atlas, including detailed information on the solar potential of the individual buildings in the state (LUBW, 2013). Despite the challenges for small cities, smaller communities can make public engagement easier.

From an electricity system perspective, distributed solar PV generation can provide benefits, particularly at low penetration levels. Solar PV generation, reaching its maximum output around noon, can contribute to possible peak loads in the middle of the day, e.g. in hot climates from air conditioning. RTSPV is also located close to demand, thus reducing transmission losses and generation needs from the national system. In the longer term, deployment of these systems may result also in lower investment needs for transmission or centralised generation.

With increasing penetration and feed-in into the distribution grid, RTSPV may also create challenges to the electricity system. Power generation around noon may exceed the local load, thus requiring backflows in the grid. The high demand density of cities could help to address these challenges. Surplus PV generation may be absorbed by smart-charging of EVs or stationary batteries, or converted in power-to-gas plants into gas, in electrolysers into hydrogen, or in heat pumps into heat, which can be used for district heating or cooling.

Many countries are seeing a rise in the number of consumers installing RTSPV systems and becoming "prosumers" by producing electricity and consuming it or exporting it to the grid. Decision makers have started introducing supportive policies, such as net metering for RTSPV systems, to promote prosumer involvement with the grid. Globally, prosumers have the potential to help mitigate growing energy supply-demand gaps, particularly at the city level, where consumption is set to rise with rapid rates of urbanisation. The introduction of programmes supporting RTSPV in cities is, however, not without problems, with challenges not necessarily linked to the specific support mechanism (Box 6.1).

Box 6.1 Prosumers in Bangalore: Lessons and barriers for scaling RTSPV

Bangalore, India's fourth-largest city located in the state of Karnataka, shares similar struggles meeting electricity demand with many rapidly growing cities in developing countries. Recently BESCOM, Bangalore's main utility with 8.9 million customers, has failed to meet peak demand – roughly 3 400 MW – by almost 900 MW (The Times of India, 2015). Scaling prosumer adoption of RTSPV through net metering is one attempt at minimising the pressures to meet demand. Given Karnataka's solar power potential of 20 GW (Government of Karnataka, 2014), solar PV presents a plausible solution, though the state's current PV target of 2 GW by 2021 is more modest (Government of Karnataka, 2014).[1]

The RTSPV market in Bangalore has steadily gained traction since the introduction of BESCOM's net metering programme in November 2014. By September 2015, 2.1 MW of grid-connected RTSPV systems were connected.[2,3] At current trends, the programme will reach a cumulative installed capacity around 44 MW by 31 March 2018 – the end of fiscal year (FY) 2017/18. This achievement would be impressive in light of the total RTSPV capacity of Karnataka of 16 MW in 2014, but would likely leave the state short of its goal of 400 MW of grid-connected solar PV by the end of FY 2017/18 (Government of Karnataka, 2014),[4] in addition to making only a small dent in India's goal of 40 GW of RTSPV by 2022.

In Bangalore, specific barriers to the successful scale-up of RTSPV under the net metering programme include:

- **Limited reach and financial appeal of the net metering programme:** The net metering programme is attractive and attainable only to a small, wealthier and motivated segment of the population, limiting the programme's potential reach and growth. This barrier is further aggravated by a lack of financial support and financing options for residential prosumers. Many of those participating in the programme have self-financed their systems. Furthermore, the rate being offered under the net metering programme (9.56 rupees (INR) per kilowatt hour (kWh) or USD 0.14/kWh) is not particularly attractive. Participation in the programme is driven more by environmental awareness than financial gains.

To expand the limited reach and financial appeal of the programme, government agencies and banks need to facilitate and promote current subsidy and loan programmes (e.g. accelerated depreciation, interest rate subventions), especially for those who do not have sufficient up-front funds.

- **Poor understanding of PV technology and the net metering programme by average citizens:** Average residents lack a basic understanding of solar PV technologies – how they perform, their costs, and how they can translate into payments through the net metering programme. Furthermore, a lack of clarity exists for both prosumers and developers about certain specifications of the net metering programme. For example, confusion exists about whether a hybrid RTSPV system – a grid-connected RTSPV system with battery backup – is allowed.[5] The lack of understanding threatens the potential growth of RTSPV and net metering programmes.

  BESCOM has started disseminating information about the net metering programme through newspaper and radio ads, but more can be done and more frequently. Programme administrators, city officials and government agencies could not only promote the technology and the programme, but also highlight community champions and stories of successful systems.

- **Uncertainty in project developer selection and interaction:** Potential new prosumers are often reliant on project developers and programme administrators for information and clarification on the programme. In August 2015, more than 51 developers had been involved in installing a little over 100 RTSPV systems under BESCOM's net metering programme. Ultimately, the number of developers points to a lack of market maturity and lack of experience of the developers, creating uncertainty for customers in choosing and trusting one developer over another.

  To improve prosumers' trust in project developers, programme administrators can provide clearer and more transparent guidance around quality by offering free and open certification processes to developers who want to provide RTSPV services and products.

- **Limited institutional capacity of the programme administrator:** Bangalore's net metering programme is relatively new and is suffering from natural growing pains. As more prosumers participate in the programme, limitations within BESCOM are starting to become apparent, such as longer wait times for interconnection appointments and meter reading processes. BESCOM acknowledges these limitations and realises that it is learning as it gains more experience with the programme.

  Capacity issues can be addressed and strengthened by programme administrators in the short term through streamlined approval processes. In the longer term, programme administrators can create a "one window" net metering unit that manages the entire process from application to payments. Better training of employees on specialised skills could be a further long-term initiative.

Understanding how programmes are being implemented, how consumers are being engaged, their level of awareness, and their experience with the programme are all important in creating and maintaining a successful RTSPV programme that can meet state and national goals.

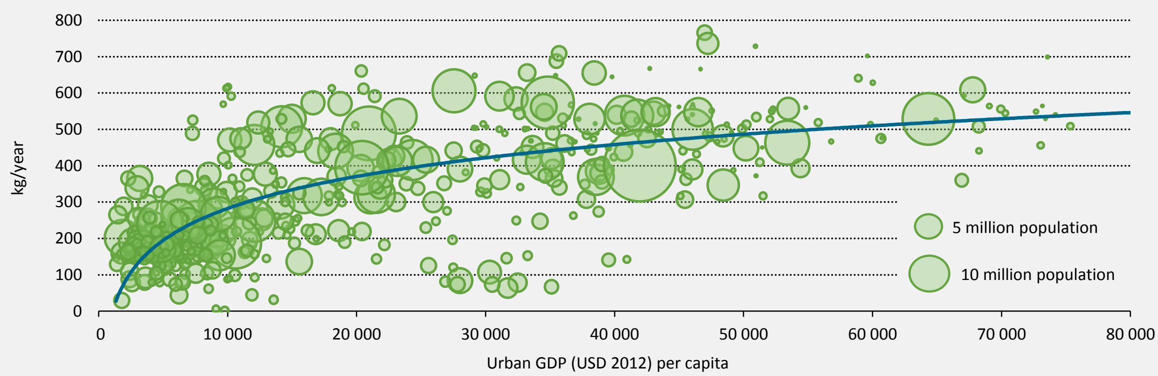
Notes:
[1] Karnataka's solar policy claims a "market potential" of 10 GW for solar power in Karnataka.
[2] The most recent data are available at http://bescom.org/wp-content/uploads/2015/08/WEB.pdf.
[3] India's total installed RTSPV capacity reached 350 MW by June 2015 (Bridge to India, 2015).
[4] Some ambiguity surrounds the RTSPV goal. In one place the policy states, "It is proposed to achieve a minimum 400 MW of grid connected roof top solar generation projects in the state by 2018", but then includes "grid connected and off grid" projects in the year-wise goals (Government of Karnataka, 2014).
[5] Hybrid RTSPV systems with battery backup are attractive to prosumers because these systems allow prosumers to store excess generation when the RTSPV system and the grid cannot provide power – for example, at night and during power cuts. The authors were informed at a meeting with BESCOM officials on 24 July 2015 that batteries and hybrid inverters were recently approved by the technical committee to be allowed as part of the net metering programme, and that at least one such system has already come on line.
Source: This case study was submitted by Sarah Martin and Josh Ryor from the World Resources Institute (WRI).

Waste-to-energy potential in cities

Using waste as a source of energy is not a new technology. As early as the 19th century, waste incinerators were used to generate mechanical energy or electricity. In absolute numbers, the role of waste in the energy system is rather modest. In 2013, waste (renewable and non-renewable fractions) accounted for less than 0.4% of total primary energy demand. In the power sector, WTE plants accounted for around 16 GW, or less than 0.2% of the total installed capacity in the world. Despite this minor contribution to the total energy system, WTE can play an important role in parts of the energy system. In Denmark, 18% of the district heat generation was based on MSW in 2013. WTE also plays an important role in the waste management strategies of cities. For example, in its 12th Five-Year Plan (FYP), China pursued the objective of increasing the share of urban household waste treated in WTE plants from 20% in 2010 to 35% in 2015. Growing waste volumes resulted in an eightfold of the Chinese WTE capacity to 4.5 GW by 2015.

The amount of waste generated in cities strongly depends on the income levels of the urban population, as shown in Figure 6.6 for a dataset of around 600 cities worldwide. The average Indian urban dweller generates around 100 kilogrammes (kg) of MSW per year at an income level of around USD 6 000 per year, while in Japan, with an average urban income of USD 37 000, an urban inhabitant produces around 430 kg per year.

Figure 6.6 **Urban MSW generation per capita as a function of urban income levels**



Note: Sizes of the bubbles correspond to the cities' population in 2012.
Sources: IEA analysis with urban GDP per capita and population data from *McKinsey Global Institute Cityscope v2.55*.

Key point *MSW generation per capita is strongly driven by income, with saturation levels being reached at higher income levels.*

WTE is an integral component of waste management strategy, but it is not the sole option. Following a broadly accepted waste management hierarchy, measures to avoid waste and to recycle valuable waste fractions are the preferred steps. Only the remainder is combusted in WTE plants. Landfilling is the least preferable option and should be reduced to a minimum, mainly because it uses land. If not managed properly, landfilling can also pollute the local environment and contribute to global warming through methane emissions, or so-called landfill gas. The impact of the latter, though, can be reduced by recovering the landfill gas and using it for energy purposes.

Many cities in developing and emerging economies are still far from this ideal strategy. Not all waste generated is collected, posing health risks. Collected waste is often dumped in open, poorly managed landfills, creating environmental and again health risks. National governments are responsible for developing legislation for modern waste treatment and for ensuring its enforcement. In this context, governments and cities should seek to integrate the informal waste picking and recycling sector into their waste management plans. In Delhi, 27% of the city's waste is collected by informal waste pickers (Gupta, 2012). Municipalities can support the formation of co-operatives of waste pickers and partner with them.

WTE is not an uncontested technology. Concerns about air pollutants are often stated as arguments against WTE. The reason for this opposition has its origins in early plants with often poor treatment of stack emissions, which led to closure of plants in the United States in the 1960s and 1970s (Klinghoffer and Castaldi, 2013). In China in 2015, the population in the city of Hangzhou protested against the construction of a waste incinerator because of concerns about air pollution (Economist, 2015). Governments and municipalities should not only enforce strict emissions standards for WTE plants, but should also inform the public about the possible safe operation of WTE. The potential can be seen in countries such as Japan, where 74% of MSW is used for WTE, and Switzerland, with a 49% share (Hoornweg and Bhada-Tata, 2012).

Several technologies are available to convert MSW feedstocks into heat and electricity. Methods include direct combustion, gasification, pyrolysis and anaerobic digestion. Of the several technologies for converting MSW to energy, mass burn is the most common, which directly combusts MSW as a fuel with minimal processing (Funk, Milford and Simkins, 2013), using fixed-bed grate or stoker furnaces or fluidised-bed systems. For both combustion systems, flue gas treatment measures have to be taken to minimise air pollution. Due to the cost of air pollution control equipment, WTE plants are usually deployed only at sizes above 10 megawatts electrical (MW_e), which means that WTE makes sense only for larger municipalities (100 000 tonnes MSW per year for WTE) or by combining the waste volumes of smaller cities. Available waste volumes limit the size of WTE plants, so that today more than 70% of operating WTE plants in the world are in the size range of 10-50 MW_e (Coenrady, 2013).

Refuse-derived fuel (RDF) refers to loose or pelletised fuel derived from processed waste, which is then burned on its own or co-fired with other fuels (coal, biomass). Due to lower investment cost requirements, co-firing of waste in coal or biomass power plants can be an attractive alternative to building a dedicated WTE plant (Klinghoffer and Castaldi, 2013).

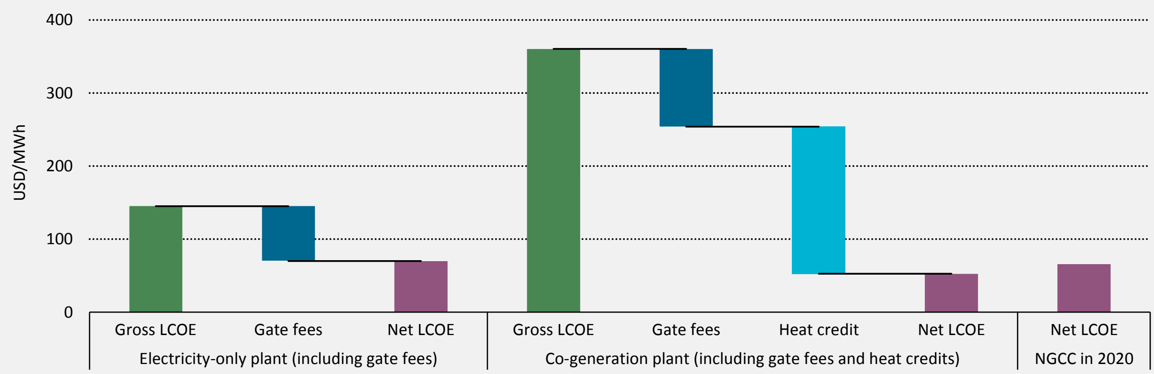
Pyrolysis and thermal gasification involve decomposition of waste at a high temperature with little or no oxygen to generate a synthesis gas, which can then be used after clean-up of the gas for the production of electricity, heat, fuels or chemicals. Flexibility in the uses of the resulting synthesis gas is one of the advantages of gasification over combustion. Also, the gas clean-up system can be smaller compared with a combustion process as less air is introduced in gasification. Despite these advantages, gasification technologies are still under development, with around 100 plants in operation today with an annual waste-processing capacity of over 4 million tonnes of MSW.

Typical net electricity conversion efficiencies of WTE plants are in the range of 20-30%, which is rather low compared with biomass or coal power plants. An alternative option is to burn MSW in co-generation plants, producing both electricity and heat. Compared with an electricity-only WTE plant with an electric efficiency of 25%, the total energy recovery in co-generation plants can be raised to 85-105%, with the loss in electrical efficiency being only 3-6 percentage points.[10]

10 Efficiencies are based on LHV. Condensing the water in the flue gas below its dew point can lead, depending on the water content of the MSW, to efficiencies of above 100% on a LHV basis.

In Europe, specific investment costs for WTE plants using grate-firing are USD 6 500 per kilowatt electrical (kW_e) to USD 16 000/kW_e, depending on the plant size. Just based on these capital costs, the levelised costs of electricity (LCOE) of WTE plants could not compete with those of other electricity generation technologies (shown as gross LCOE in Figure 6.7). Additional revenue streams through gate or tipping fees, which are paid to plant owners for taking the waste, or through heat credits by selling district heat, reduce the net costs of WTE plants (shown as net LCOE in Figure 6.7) and are important for their economic operation.

Figure 6.7 LCOE for WTE technologies



Notes: Illustrative example for a WTE plant in Europe with the following techno-economic assumptions: investment costs USD 8 500/kW_e, fixed operating and maintenance costs USD 255/kW_e, variable operating and maintenance costs USD 9 per megawatt hour electrical (MWh_e), construction time two years, economic lifetime 25 years, discount rate 8%, electric efficiency 19% and heat efficiency 79% for co-generation plant, electric efficiency 27% electricity-only plant, full-load hours 3 000 for co-generation plant and 7 500 for electricity-only plant, gate fees USD 20/MWh_{waste}, heat credit USD 52 per megawatt hour heat (MWh_{heat}); natural gas combined-cycle plant with investment costs USD 1 100/kW_e, fixed operating and maintenance costs USD 27/kW_e, construction time two years, economic lifetime 35 years, discount rate 8%, electric efficiency 57%, gas price USD 8 per million British thermal units (MBtu).
Source: IEA analysis based on data from Elforsk (2014), *Electricity from New and Future Plants 2014*; JRC (2014), *ETRI 2014: Energy Technology Reference Indicator Projections for 2010-2050.*

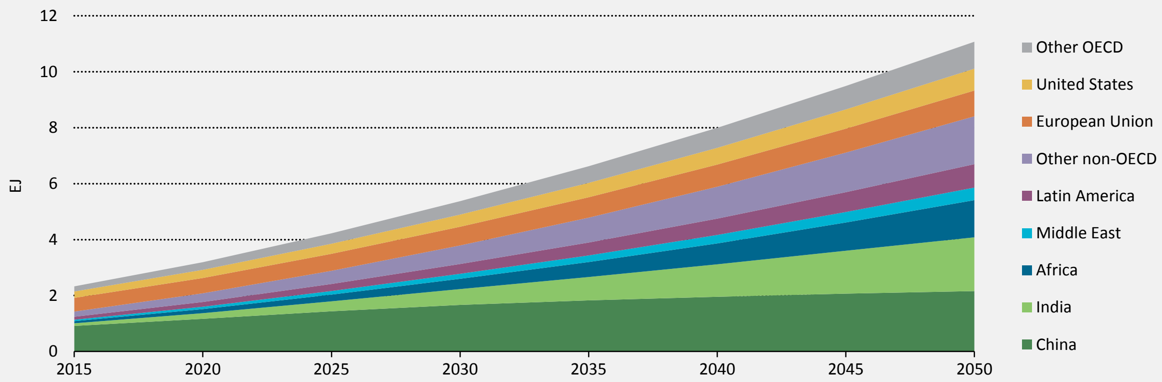
Key point *Gate fees for waste treatment and heat credits from selling district heat are crucial for the economic viability of WTE plants.*

Gate fees for MSW, which are paid to WTE plant operators for taking the MSW, are driven by the cost of waste landfilling.[11] Further revenues can be generated when WTE plants can sell district heat. The lower full-load hours of co-generation plants result in higher gross LCOE compared with an electricity-only operation with higher full-load hours, but this cost increase in gross LCOE may be offset by additional revenues from selling heat, depending on the heat tariff.

For the *ETP* scenario analysis, the overall global urban MSW potential available for WTE has been estimated to be 11 EJ in 2050 (Figure 6.8).[12] This amount represents 4% of the fuel input in the power sector in the 2DS in 2050. Comparing this percentage with the current share of less than 0.4% illustrates that MSW from the technical potential point of view could play a bigger role in the future.

11 In 2011, landfill charges in EU countries varied widely from EUR 3/t in Bulgaria (USD 1.3/MWh_{waste}) to EUR 155/t in Sweden (USD 67/MWh_{waste}) (EC, 2012).
12 See online Annex I at www.iea.org/etp/annexes for details on the estimation.

Figure 6.8 Urban MSW potential for WTE on a primary energy basis by region



Key point *Urban MSW has the potential to provide more than 10 EJ of primary energy in the future, an amount corresponding to the current total primary energy use of Brazil.*

The global technical potential of urban MSW is 830 TWh of electricity and 2 400 TWh of district heat. These totals are small[13] compared with the global electricity needs of cities in 2050 in the 2DS of more than 26 000 TWh.[14] Still, the generated electricity and district heat from waste can provide additional revenue for often publicly owned waste management companies.

Energy recovery at wastewater treatment plants

Demand for water is going to increase by 2050, driven by economic growth and increase in population. Global water demand for domestic use alone could reach 790 cubic kilometres (km^3) by 2050, more than a doubling compared with 2000 (OECD, 2012). As for energy, urban areas will play a major role in this demand growth for water. Wastewater treatment (WWT) and reuse of water will become more and more important to reduce the pressure on freshwater supplies. Recovering energy from municipal wastewater streams can help to reduce the costs of these WWT efforts.

The main options to recover energy at WWT plants are to use the thermal heat in the wastewater for low-temperature heating or cooling (e.g. district heating after upgrading the heat in a heat pump) and to process the chemical energy of the organic matter in the wastewater through anaerobic digestion into fuels, such as methane or hydrogen (Box 6.2).

Future treated wastewater volumes have been derived from data on current municipal wastewater produced, treated and collected in the AQUASTAT database of the Food and Agricultural Organization (FAO) (FAO, 2015) in combination with urban population and gross domestic product (GDP) projections. Based on these assumptions, estimates indicate that globally around 185 TWh of electricity and 280 TWh of heat could be generated from sewage gas by 2050, while the upgrading of excess heat in electric heat pumps would provide 460 TWh of heat.[15]

13 Assuming all urban MSW would be burned in co-generation plants with an electric efficiency of 19% and a heat efficiency of 79% in back pressure mode.

14 Overall, global district heating demand is, at 2 500 TWh in 2050, closer to the MSW potential of 2 400 TWh, but this is misleading, since the demand potential for district heat depends on the climate conditions – i.e. in a hot climate, no demand exists for the condenser heat of a WTE plant. If entirely used for district cooling through absorption chillers, the heat of 2 400 TWh would provide a cooling energy of 3 860 TWh (based on a coefficient of performance of 1.6).

15 See Annex I under www.iea.org/etp/annexes for a detailed description of the underlying calculation to estimate these potentials.

Box 6.2 Urban energy supply options from organic waste in Xiangyang, China

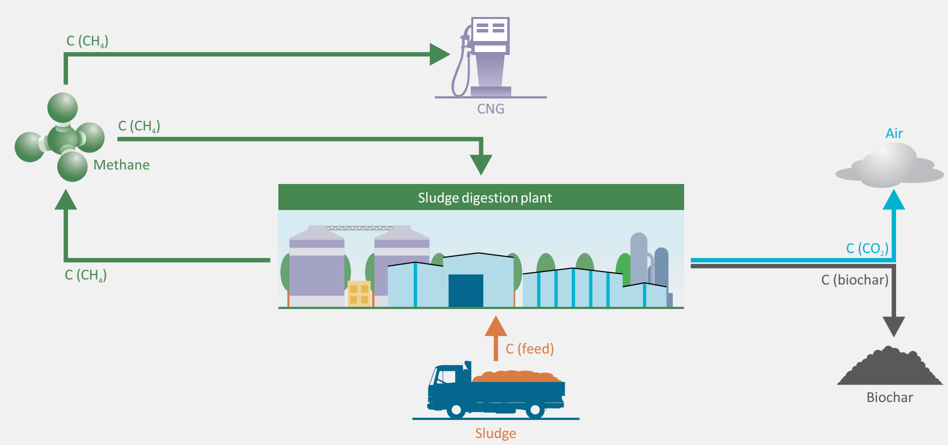
Effective and sustainable disposal of wastewater sludge has been a challenge in countries experiencing rapid urbanisation, such as China. China's municipal WWT plants are projected to produce over 30 Mt of sludge by 2015, but less than 20% is expected to be retreated. This situation represents an environmental problem, but at the same time an opportunity for capturing significant amounts of energy and greenhouse gas (GHG) emissions. Xiangyang City of Hubei Province – a medium-sized city in China with just over 1.4 million people – has invested in and tested a "high-temperature thermal hydrolysis + highly concentrated anaerobic digestion + methane capture and utilisation" process, with the capacity for the co-digestion of 200 t per day of sewage sludge and 100 t per day of organic kitchen waste (Figure 6.9).

Since its operation started in 2012, the project has successfully accomplished multiple goals, ranging from the complete treatment of sludge to the generation of renewable energy and the recovery of a nutrient-rich resource through a cost-effective treatment process:

- Recovery includes 96% nitrogen and 98% phosphorous in the form of a nutrient-rich biochar fertiliser. In the last two years, 432 000 saplings have been grown as a result of applying biochar to 800 km^2. The carbon sink capacity of the trees planted is estimated to be about 751 million tonnes of carbon dioxide ($MtCO_2$).
- Compared to other waste disposal strategies, such as incineration or landfilling, GHG emissions can be reduced by 95%, resulting in estimated reductions of 13 million tonnes of carbon dioxide equivalent ($MtCO_2$-eq) over the course of the 21-year project lifetime.
- Over the project lifetime, 45 million cubic metres (m^3) of compressed natural gas (CNG) can be produced, replacing 48 000 m^3 of gasoline.

The Xiangyang project is demonstrating the importance of designing a project and selecting technologies with a complete value chain view and a strong emphasis on market needs to secure the sustainability of the project's capital flow. The project received financial support from the municipal government of Xiangyang, an international financial organisation, and the Export-Import Bank of China. This arrangement created a "government-bank-enterprise" partnership, which was essential for working out long-term contractual agreements and harmonising the interests among the three parties. The Chinese government is promoting the technology across the country, with more than ten cities, including Beijing, Tianjin and Shanghai, considering its use.

Figure 6.9 Overview of the organic waste treatment process



Key point *Sewage sludge and kitchen waste are converted into marketable products, CNG and biochar.*

Source: This case study was submitted by Lijin Zhong, Xiaotian Fu and Rodrigo Villarroel Walker from the World Resources Institute (WRI).

The overall energy potential of the energy recovered at WWT plants is admittedly very small compared with the overall energy needs of a city. But since energy is required to operate WWT plants, energy recovery from WWT can provide cost savings to the operators of these plants, which are often public entities. On average, around 12 kWh of electricity per capita and per year could be generated from sewage gas at WWT plants. Depending on the size of the WWT plant, this level of electric generation corresponds to 40% to 65% of the energy consumption needed for WWT (Drechsel, Qadir and Wichelns, 2015). These energy cost savings are important against the background of an expected increase in water consumption in emerging and developing countries, not only due to growing income levels, but also in the effort to reach the sustainability goals of universal access to water, sanitation and energy.

Excess heat from industrial processes

IEH delivered through thermal networks can be an additional energy source for urban and other industrial users. Not all energy consumed in an industrial site is effectively used in the manufacturing process. Part of the energy input leaves the industrial process in the form of flue and exhaust gases, solid and liquid industrial streams, and heat dissipated from hot equipment surfaces. IEH can be defined as the heat content of all streams leaving an industrial process at a given moment in time (Berntsson and Asblad, 2015).

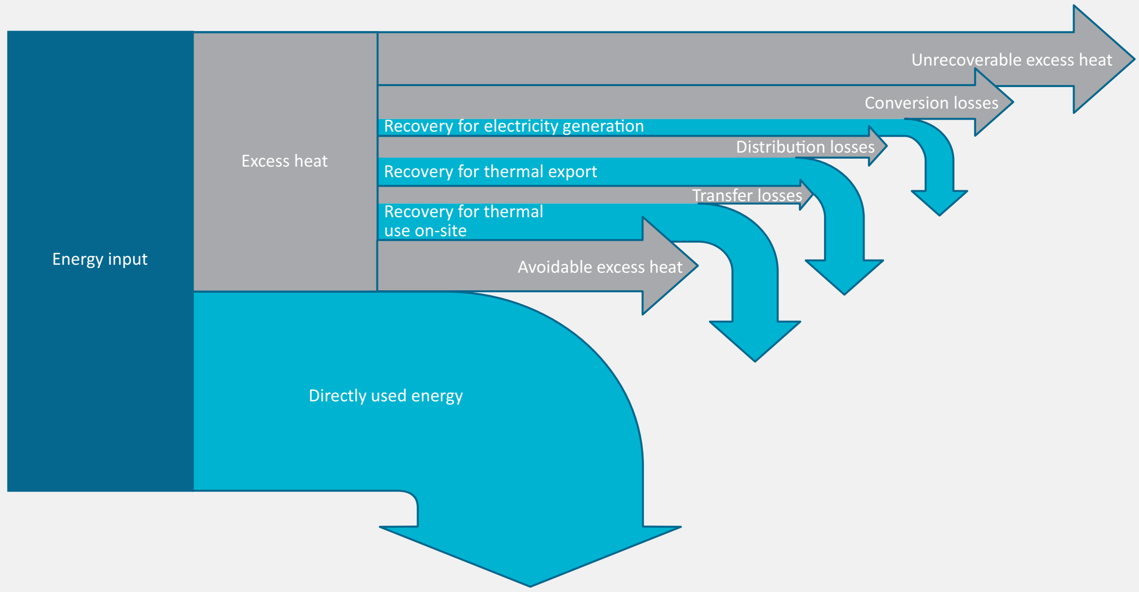
The extent to which heat can be technically and economically recovered depends on the characteristics of the IEH sources (such as cleanliness, temperature level and intermittency of supply) as well as the availability of an end use. From an energy efficiency perspective, IEH generation should be minimised in the first place through limiting process temperatures, improved process control and maintenance, and enhanced equipment insulation. After reaching the economically effective level of process optimisation, diverse applications of recovered IEH can be considered: direct use on site, export to local DHC networks supplying energy to urban areas or to neighbouring industrial facilities, or electricity generation (Figure 6.10).

Several studies have estimated national and regional IEH inventories. Assessment methodologies are diverse, and results vary widely, with IEH inventories ranging from 20% to 70% of the country's final industrial energy consumption. These ranges are wide even though the contribution of energy-intensive industries to total national industrial energy use does not vary so greatly across countries, reinforcing the importance of the approach taken.

Energy-intensive industrial sectors[16] tend to be more excess heat-intensive, provided involved processes have greater specific energy requirements and operating temperature levels. Energy-intensive sectors in Europe represent 48% of industrial heat demand between 100°C and 400°C (medium temperature) and 91% of industrial heat demand above 400°C (high temperature) (Werner, 2006). For instance, a study performed for the United Kingdom concluded that the iron and steel, aluminium, and cement sectors have the greatest estimated average heat recovery potential in that country with 2.7 PJ/site, 0.6 PJ/site and 0.3 PJ/site, respectively, compared with a total industry average of 0.1 PJ/site (McKenna and Norman, 2010). Similar results are confirmed by other studies: energy-intensive sectors represented around 83% of the identified IEH in Norway (Sollesnes and Helgerud, 2009). Existing national and regional studies have also concluded that the greatest IEH recovery potential is found in medium- and high-temperature ranges (i.e. above 100°C) (McKenna, 2009; Blesl, Ohl and Fahl, 2011).

16 Energy-intensive sectors refer to iron and steel, non-metallic minerals, chemicals and petrochemicals, pulp and paper, and non-ferrous metals.

Figure 6.10 IEH management and possible uses



Note: Illustrative sketch of an industrial process not at scale. Levels of directly used energy vary depending on the type of process and site-specific practices and constraints. *Unrecoverable excess heat* refers to excess heat whose recovery cannot be economically justified. Thermal transfer losses are typically negligible compared with distribution or conversion losses.
Source: Developed from Forni, D., D. Di Santo and F. Campana (2015), *Innovative System for Electricity Generation from Waste Heat Recovery*.

Key point *Maximising energy efficiency should drive IEH management.*

Recovering low-temperature excess heat typically poses additional challenges because greater heat transfer surface area is required, which translates to higher capital investment costs and a greater chance of reaching space constraints in the industrial site. Finding a compatible end use for low-temperature recovered excess heat can be limiting in some industrial activities. In these cases, external end uses or the implementation of upgrading technologies (e.g. heat pumps) need to be explored (Kumar and Karimi, 2014). Alternative electricity generation technologies are emerging to make use of low-temperature heat such as organic Rankine cycles (ORC) or Kalina cycles, among others. These technologies operate with low boiling temperature working fluids, enabling the use of lower-quality heat sources.

Assessing the potential for low-temperature IEH recovery is especially complex given the larger number of possible sources and the greater impact of site-specific characteristics and ambient conditions. Site-level process integration becomes even more relevant to identify additional energy savings from low-temperature sources. For instance, process integration techniques, including pinch analysis,[17] could deliver 5% additional energy savings, compared with best-practice energy performance, in the petrochemical and chemical sector (Saygin et al., 2011).

Within energy-intensive sectors, the IEH recovery potential from medium- and high-temperature sources in the chemicals and petrochemicals and in the pulp and paper sectors is considered more limited. This limitation exists because the industrial processes involved operate at lower temperatures on average compared with other energy-intensive industrial sectors, and because these processes already have a considerable level of process

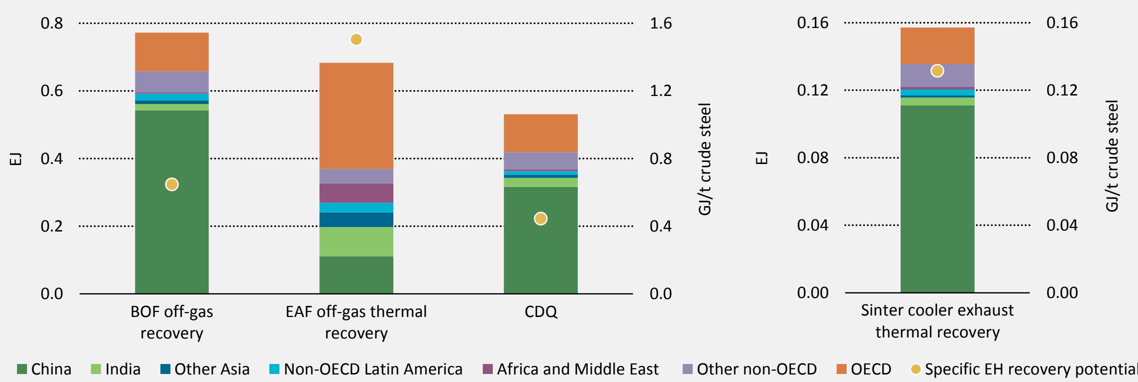
17 Pinch analysis consists of generating composite curves by aggregating *hot streams* to represent the total heating demand of a system and *cold streams* to represent the total cooling demand. The point at which the curves are closest is called the *pinch*, and the area between both curves represents the maximum heat recovery as a function of temperature.

integration. For instance, recent studies did not identify IEH recovery potential above 150°C from ethylene crackers in the United States (BCS Incorporated, 2008).

A technical potential assessment was performed for IEH recovery from medium- and high-temperature sources, where previous studies identified the greatest IEH potential.[18] The approach consisted of exploring commercially available recovery technology options within this temperature range, which led to identifying the greatest opportunities in the iron and steel, cement, and aluminium sectors among the energy-intensive industrial sectors. Each application was characterised with a technical energy recovery potential level considering technical constraints, such as minimum practical cold-end temperature of acid flue gases to avoid corrosion problems. However, recovery potentials can be further limited by operational factors such as limited effective operating time of recovery equipment.

In the **iron and steel sector**, several IEH recovery opportunities were identified under these criteria, resulting in an estimate of 2.1 EJ[19] of technically recoverable heat globally, which is 7% of the global final energy consumption in the sector (Figure 6.11).[20] Around 74% of this potential lies in non-OECD economies, which are also responsible for about 70% of the global crude steel production. China represents 50% of the identified global technical energy savings potential.

Figure 6.11 Global technical IEH recovery potential from selected applications in the iron and steel sector



Notes: CDQ = coke dry quenching, EAF = electric arc furnace, EH = excess heat. Technical IEH recovery potentials refer to 2013 industrial stock. Specific energy savings in GJ/t crude steel refer to the relevant share of global crude steel production: crude steel production via BF and BOF for CDQ, BOF off-gas recovery and sinter cooler exhaust thermal recovery, and crude steel via EAF for thermal recovery from off-gas generated in this process. Thermal energy recovery from hot stove exhaust gas is not included in the global technical recovery potential assessment due to lack of regional implementation information.
Sources: IEA analysis based on Table 6.1 and IEH recovery technologies regional implementation levels from Hongyou, L. (2015), *Capturing the Invisible Resource: Analysis of Waste Heat Potential in Chinese Industry and Policy Options for Waste Heat to Power Generation*; Rock, M. and M. Taman, (2015), *China´s Technological Catch-up Strategy: Industrial Development, Energy Efficiency and CO_2 Emissions*; and IEA estimates.

Key point *2 EJ, or 1.3 GJ/t crude steel, could be technically recovered in the iron and steel industry globally.*

Recovering the sensible[21] and chemical energy from the off-gas generated in BOFs represents the greatest overall energy savings opportunity within the selected IEH recovery technologies: 0.8 EJ potential energy savings globally. This recovery system is commonly called “suppressed combustion” and is designed to recover around 70% of the BOF off-gas sensible and latent heat, 535-916 megajoules per tonne (MJ/t) crude steel (Worldsteel, 2014a).

18 See online Annex G at www.iea.org/etp/annexes for more details on the estimation.
19 Sensible heat recovery from hot stoves exhaust is not included. The basic oxygen furnace (BOF) off-gas recovery potential covers both the sensible and chemical energy from the off-gases.
20 Final energy consumption of the iron and steel sector was 32.9 EJ in 2013, including blast furnaces (BF) and coke ovens (CO).
21 Sensible heat refers to the energy exchanged by a system that varies the temperature.

CDQ recovers the thermal energy from hot coke that typically leaves the coke oven batteries at 1 000-1 100°C. Wider implementation of CDQ in global coke production could lead to 0.5 EJ technical energy savings. A considerable CDQ implementation level of about 50% in China, responsible for more than 65% of global coke production, is pushing the global penetration of this technology to about 44%.

Recovering IEH from the sinter cooler exhaust and sinter strands, and from the off-gas generated in EAFs, represents 0.8 EJ technical energy savings globally. While IEH recovery from the sinter-making process is widely implemented in countries such as Japan and Korea, the application of IEH recovery in EAFs is rare mainly because of significant capital investment requirements. The intermittency of EAFs that operate in batch mode poses additional challenges to the implementation of recovery technologies.

Assessing the global technical potential of the wide implementation of IEH recovery from stove exhaust was not possible because of lack of robust information on current regional implementation levels. In China, 5% of the BF-BOF-based crude steel production is estimated to be equipped with heat recovery technology in hot stoves (Huang, 2013), and a wider implementation would lead to 0.16 EJ of technical thermal energy savings.

Electricity can also be generated from the recovered thermal energy through the recovery technologies. IEH recovery in hot stoves can be an exception, where the lower exergy[22] level of recovered thermal energy limits the typical use of this additional available energy to pre-heating purposes. For instance, in 2013, the first application of an ORC recovering heat from exhaust gases of an EAF was implemented in Germany with a 2.56 MW design net electricity generation capacity. The variability and intermittency of the EAF process were solved by installing a steam drum that provided thermal storage capacity (Forni, Di Santo and Campana, 2015).

Table 6.1 **Main commercially available medium- and high-temperature IEH recovery opportunities in the iron and steel sector**

IEH recovery process	Hot end IEH source temperature (°C)	Cold end IEH source temperature (°C)	Technical thermal recovery potential (MJ/t crude steel)	Technical electricity generation potential (kWh/t crude steel)
Sensible heat recovery through CDQ	980	130	1 700-1 800 MJ/t dry coke	140 kWh/t dry coke
Sensible and chemical heat recovery from BOF off-gas***	1 200	250	535-916*	54-92
Sensible heat recovery from EAF exhaust gas	1 100-1 200	<250	1 548	130
Sensible heat recovery from hot stove exhaust	150-300 (during on gas phase)**	<100	280-188 MJ/t pig iron	N/A
Sensible heat recovery from sinter cooler exhaust gas and sintering strands off-gas	380-430	<180	179 MJ/t sinter	18-20 kWh/t sinter

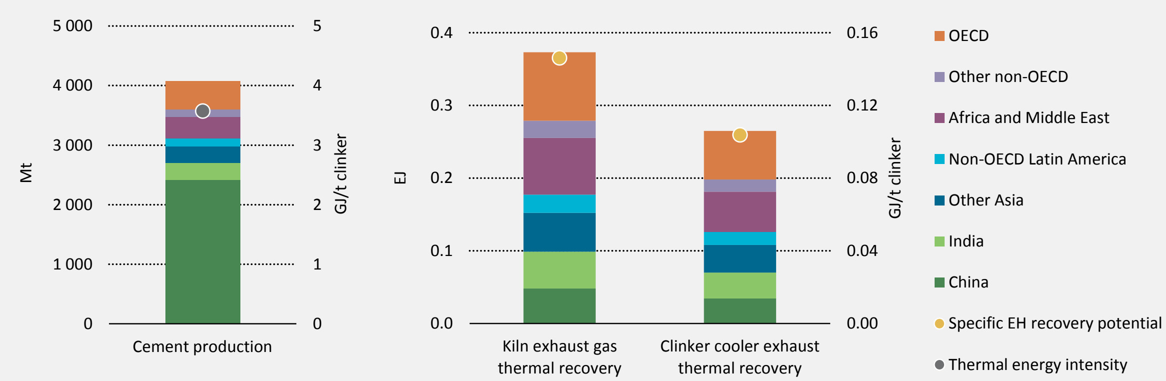
* Thermal recovery potential varies depending on the amount of BOF gas generated (50-100 normal cubic metres per tonne [Nm^3/t] crude steel) and its net heat content (7-10 megajoules per normal cubic metre [MJ/Nm^3]). ** Heating air in hot stoves consists of a regenerative process with two phases: *on gas*, when hot stove is heated by the burner, and *on blast*, when air flows through the heated brick work. *** This IEH recovery option refers to suppressed combustion systems that enable the recovery of about 70% of the sensible and chemical heat content of BOF off-gas.
Notes: kWh/t = kilowatt hour per tonne. The table is not intended to be an exhaustive list. Thermal recovery and electricity generation potentials consider technical constraints derived from the characteristics of IEH sources and practical experience.
Sources: Worldsteel (The World Steel Association) (2014a), *Energy Use in the Steel Industry*; MEA (Ministry of External Affairs of India), MoEF (Ministry of Environment, Forest and Climate Change of India), METI (Ministry of Economy, Trade and Industry of Japan) and JISF (Japanese Iron and Steel Federation) (2013), *Technologies Customized List for Technology Transfer to Indian Iron and Steel Industry with Regard to Energy-Saving and Environmental Protection* and IEA estimates.

22 Exergy is a measure to indicate to what extent energy is convertible to other forms of energy.

In the production of **cement**, the calcination of limestone to lime for clinker-making in a kiln is the most energy-intensive process. Different moisture content of raw materials leads to contrasting energy requirements for clinker-making: almost 5.9-6.7 gigajoule per tonne of clinker (GJ/t clinker) for the wet process and 4.6-2.9 GJ/t clinker[23] for the dry process (IEA, 2007).

State-of-the-art dry-process kiln systems already include IEH recovery techniques to make use of part of the thermal energy of kiln flue gases to preheat raw material[24] and of the air to cool the clinker down as secondary combustion air. Depending on the moisture content of raw materials, opportunities for further thermal energy recovery can be found in the dry clinker-making process (Table 6.2). For instance, 0.6 EJ can be technically recovered globally from kiln and clinker cooler exhaust gases when the process involves raw materials with low moisture content of 2-6% and a five-stage preheater cyclones and pre-calciner kiln configuration (Figure 6.12). In non-OECD economies, 78% of the identified global technical potential could be saved, or 0.2 GJ/t dry-process-based clinker, which accounts for 88% of global cement production. A specific thermal recovery potential of 0.4 GJ/t dry-process-based clinker is estimated for OECD economies, where recovery technology implementation levels are moderate, except in some countries such as Japan and Korea. However, the estimated technical potential can be limited in regions typically operating with raw materials of high moisture-content levels such as Russia.

Figure 6.12 Global technical IEH recovery potential from selected applications in the cement sector



Notes: Technical IEH recovery potentials refer to 2013 industrial stock. Specific energy savings in GJ/t cement refer to global dry- process-based clinker production.
Sources: IEA analysis based on Table 6.2 and IEH recovery technologies regional implementation levels from Hongyou, L. (2015), *Capturing the Invisible Resource: Analysis of Waste Heat Potential in Chinese Industry and Policy Options for Waste Heat to Power Generation*; BCS Incorporated (2008), *Industrial Waste Heat Recovery: Technology and Opportunities in U.S. Industry*; IIP (Institute for Industrial Productivity) and IFC (International Finance Corporation) (2014), *Waste Heat Recovery for the Cement Sector: Market and Supplier Analysis*; Izumi, Y. (2014), "Role of the Japanese Cement Industry in the Establishment of a Sustainable Society"; Ojan, M. (2015), "Solar Power and New Concrete Applications: A Pilot Plant in Morocco"; and IEA estimates.

Key point *0.6 EJ IEH or, 0.2 GJ/t dry-process-based clinker, could be technically recovered in the cement industry globally.*

After drying and preheating raw materials in the clinker-making process for a given moisture content, no additional thermal needs are compatible with the exergy level of the technically recoverable IEH from kiln flue gas (320°C) and clinker cooler exhaust

23 The range of thermal energy intensity related to the dry-process clinker-making covers from a long-dry process to a six-stage preheater and pre-calciner rotary kiln.
24 The number of cyclones of a dry rotary kiln is determined by the moisture content of the raw materials. Each additional preheating stage increases the level of thermal recovery.

(250°C) since raw materials need to heated up to 1 450°C. For this reason, cement producers need to justify the implementation of wider IEH recovery by exploring external possible end uses for the recovered energy, such as neighbouring industrial facilities or local existing or planned DHC networks. Another alternative is the use of recovered thermal energy to generate electricity, which has been widely deployed in some regions (especially China, see Box 6.3). This marginally[25] low-carbon electricity generation method can become a sustainable solution in areas with unreliable electricity supply. Practical experience shows that up to 18% conversion efficiency can be reached for electricity generation from thermal energy recovered by this method for 1 Mt/yr capacity kilns (Italcementi, 2015).

Table 6.2 Main commercially available medium- and high-temperature IEH recovery opportunities in the cement sector

IEH recovery process	Hot end IEH source temperature (°C)	Cold end IEH source temperature (°C)	Technical thermal recovery potential (MJ/t clinker)	Technical electricity generation potential (kWh/t clinker)
Sensible heat recovery from kiln exhaust gas*	320	180	298	14.9
Sensible heat recovery from clinker cooler exhaust air	250	90	212	10.6

* Estimates refer to a dry-process kiln with five stages of preheater and pre-calciner and to raw materials with a moisture content of 26% (low range). Moisture content in raw materials can reach levels even greater than 10%, in which case the thermal recovery potential is significantly reduced due to the need to use most of the recoverable IEH for drying.
Note: The table is not intended to be an exhaustive list. Thermal recovery and electricity generation potentials consider technical constraints derived from the characteristics of IEH sources and practical experience.
Source: IEA estimates developed from Italcementi (2015).

The **aluminium** sector also presents opportunities for medium- and high-temperature IEH recovery. For example, additional preheating stages can be implemented to a stationary kiln within the alumina production process from bauxite. This technical improvement in a kiln that already employs the hydrate (feed) bypass system[26] can lead to 3% (84 MJ/t alumina) energy savings from the overall process energy input (Klett et al., 2011).

Primary aluminium is produced through alumina electrolysis in Hall-Héroult cells. While energy losses through off-gases represent only 1% of the electricity input to the process, up to 45% of the energy input is discharged through cell sidewalls (BCS Incorporated, 2008). Physical constraints typically encountered in retrofitting cells, consequences of intermittent operation, and limited IEH available compared with overall process energy requirements have resulted to date in the inability of plants to develop an economical means to recover IEH from off-gases. Exhaust gases discharged by secondary melting furnaces (1 090-1 200°C) also provide a source of high-temperature IEH, although technical challenges related to the intermittency of the process and to the corrosive nature of released off-gases during fluxing[27] need to be managed (BCS Incorporated, 2008).

A global technical assessment of the IEH recovery potential in the aluminium sector was not possible because of a lack of robust information on regional technology implementation levels. However, in the United States, an estimated 8.5 PJ can be saved through the wide implementation of IEH recovery from melting furnace off-gases; an estimated 25% of

25 The marginal carbon footprint refers to the additional energy (mainly electricity) required to operate the equipment needed to recover the excess heat (e.g. pumps, fans).
26 The hydrate bypass system enables pre-calcining the feed with IEH recovered from calciner discharge.
27 During fluxing operation, impurities are removed from scrap material by adding sodium chloride and/or potassium chloride.

melting furnaces are equipped with this technology (BCS Incorporated, 2008). Assuming a 70% penetration of improved IEH recovery from calciner off-gases in alumina making in the United States currently (Kermeli et al., 2014), 0.1 PJ could be technically recovered through a broader deployment of this technology. Jointly both IEH recovery technical potentials represent less than 1% of the country's non-ferrous metals final energy consumption in 2013.

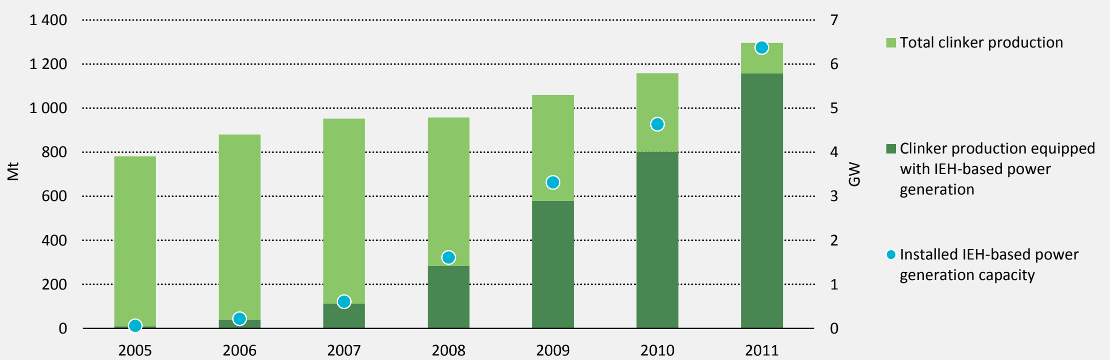
Box 6.3 Uptake of IEH recovery technologies in the Chinese cement sector

The Chinese cement sector has a history of rapid development. In 2000, dry-process preheater and pre-calciner kilns accounted for only 11% of national cement production, but by 2012 more than 90% of Chinese cement production was based on state-of-the-art dry-process kilns (CCA, 2013). Government policy and regulatory strategies have driven this significant restructuring by promoting the installation of new efficient facilities and the closure of outdated vertical shaft kilns.

Since 1998, when the first IEH-based power generation system was installed in a Chinese cement plant in Ningguo, with funding support from Japan's New Energy and Industrial Development Organisation (IIP and IFC, 2014), this technology has been massively deployed, reaching 89% of current national clinker production (Figure 6.13). Requirements for new dry-process modern kilns to install IEH power generation systems (11th and 12th Five-Year Development Planning of Cement Industry) and measures facilitating interconnection to the electricity grid (Energy Conservation Law of the People's Republic of China) have sustained this rapid deployment (IIP and IFC, 2014).

As IEH-based power generation gets closer to its full deployment potential in Chinese cement installations, domestic equipment suppliers are exploring opportunities to deploy this technology in other Asian markets. Despite the major deployment of IEH recovery technologies in the cement industry, additional benefits of directly exporting the recovered heat as thermal energy to other industrial facilities or urban areas remain unexplored to a great extent. Detailed analysis of location and quality of heating demand and production in areas of high heating-demand density may unveil opportunities for greater sustainable gains by making effective use of a larger share of recovered heat and avoiding electricity generation conversion losses.

Figure 6.13 IEH-based power generation evolution in cement sector in China



Sources: Dai et al. (2011), *China Energy Efficiency Investment Progress Report 2010* and CCA (2015).

Key point *Widespread deployment led to 89% of Chinese clinker production currently equipped with IEH-based power generation.*

In practice, deployment of IEH recovery technologies is often limited by non-technical factors. These factors include site-specific characteristics, such as local availability of a compatible end use for the recovered heat, and regional economic aspects, such as capital investment requirements, energy prices, existence of financial and fiscal supportive mechanisms of energy efficiency projects, and the foreseen industrial activity outlook. All these factors are typically put in contrast with the expectation of short payback times compared with long-living industrial infrastructure to determine the economic viability of an IEH recovery project. For instance, whereas electricity prices of USD 60/MWh-USD 70/MWh would result in a simple payback period of about four to five years for an IEH-to-power project implemented in the cement sector,[28] shorter payback periods of two to three years can be achieved with electricity prices above USD 100/MWh (Herzog and Lamare, 2013; Harder, 2013). Lack of experience in heat recovery and process integration analysis and perceived operational risks of recovery technologies can also reduce the practical implementation of these energy-saving opportunities.

Avoiding the generation of IEH through process integration and improved operating practices should be the first energy management priority within an industrial site. A long-term perspective can broaden the range of opportunities when assessing on-site compatible end uses for recovered IEH, while improving the business case of thermal recovery projects. However, optimising process operation to the economical level may still lead to the production of technically recoverable thermal losses. Exploring possible end uses outside the boundaries of the industrial facility for this rejected energy can open new sustainable business opportunities by providing additional revenues and make a positive impact on the local carbon footprint. Urban energy systems and other industrial facilities could benefit from this complementary energy resource to networks that distribute recovered IEH from industrial parks in the surrounding area to cities and other users. For instance, in a wide group of surveyed countries in Europe,[29] 63% of the energy supplied for the generation of district heat in 2013 consisted of recovered heat,[30] either from power generation facilities or industrial processes (Euroheat & Power, 2015). As a more specific example, 8% (4.9 TWh) of the energy input to the Swedish district heating system was recovered IEH in 2012 (Dzebo and Nykvist, 2015). IEH can also satisfy cooling demands through the use of absorption chillers.

The distance between end users and suppliers is one of the most critical factors to determine the viability of transporting recovered thermal energy, because it directly increases distribution thermal losses and required capital investment. A recent study associated 50% thermal losses through heat pipes to a distance of 10 km between the locations of IEH recovery and end-user demand (Hammond and Norman, 2013). However, thermal distribution losses can vary greatly depending on transportation distance, delivery temperature and system physical configuration (e.g. heat pipe diameter, insulation characteristics and maintenance protocols). Part of the identified 1 EJ medium-temperature IEH technical recovery potential globally could complement steam-based thermal distribution systems delivering energy to cities, in cases where industrial sites are located within a reasonable distance from existing or planned district heating networks.

28 Simple payback calculation based on a 10 MW IEH recovery system with 7 500 annual operating hours, USD 2 000 per kilowatt investment cost, annual operating and maintenance costs of 2.5% of capital cost, and auxiliary power requirements of 7%.

29 Surveyed countries included Austria, Bulgaria, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Hungary, Iceland, Italy, Latvia, Lithuania, the Netherlands, Norway, Poland, Serbia, Slovak Republic, Slovenia, Sweden and Switzerland.

30 Recovered heat in this survey refers to recuperated excess heat from co-generation units and to IEH. Two-thirds of the energy delivered by heat pumps is also included in this category.

The economic potential, though, will have to be analysed on a case-by-case basis, considering specific conditions of a given urban area. Recent research in energy-intensive industries located in the surroundings of 11 Chinese cities of the Hebei province estimated that 0.6 EJ of recoverable low-temperature IEH could be potentially used for district heating (Hao, 2015). Another barrier limiting the use of significant quantities of IEH in thermal distribution networks is the risk to security of supply. Unforeseen or planned disruptions in industrial activity may affect the heat delivery if IEH has a significant contribution in the network energy input and the thermal storage design capacity does not account for this circumstance.

Sustainable industrial technology options that will become increasingly important in the future, such as switching towards low-carbon alternative fuels with potentially greater drying requirements or carbon capture, among others, may find synergies with IEH recovery opportunities and limit the potential for thermal exports to urban areas or other industrial sites. For instance, in 2050, 1 692 $MtCO_2$ are captured from industrial processes in the 2DS globally. If post-combustion capturing techniques were to be used, an estimated 3.4 EJ additional thermal energy would be needed for solvent regeneration purposes. Moreover, the emergence of alternative process routes with reduced energy footprints in a low-carbon industrial future may limit the availability of IEH. For example, a significant deployment of upgraded smelting reduction and direct reduced iron processes in the 2DS would considerably lower the demand for coke making and sintering, which are processes with potential for IEH recovery today.

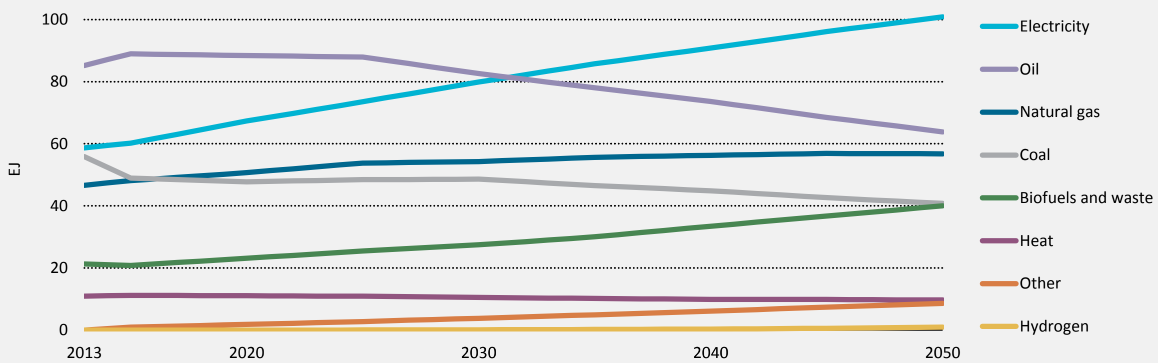
Urban electricity and heat supply in the *ETP* scenarios

Cities are already a major driver for electricity demand, accounting for 75% of global final electricity demand in 2013. In all *ETP* scenarios, urban areas maintain this share in global electricity demand, but the quantities change. In the 4DS, urban electricity demand more than doubles between 2013 and 2050. In the 2DS, this growth can be reduced to 77%, thanks to increased efficiency measures for electricity uses, and despite an increased electrification of end-use services, e.g. EVs. Electricity also plays an important role in urban areas compared with other end-use fuels, accounting today for more than 20% of global final energy needs. In rural areas, electricity accounts for only around 10% of the final energy consumed in industry, buildings, transport and agriculture. In the 2DS, this electricity share in cities increases to more than 33% by 2050, overtaking oil after 2030 in absolute terms, and becoming the largest final energy carrier in cities (Figure 6.14).

Solar rooftop PV in cities

Urban RTSPV accounts for around 47% of global electricity generation from solar PV in the 2DS in 2050, and by generating almost 2 400 TWh, it provides around 9% of the electricity consumed in cities. This generation in the 2DS corresponds to 26% of the estimated technical potential for urban RTSPV in 2050 of 9 100 TWh (8% in the 6DS and 10% in the 4DS). The contribution of urban RTSPV as a share of total urban demand varies from 27% in India to 4% in Latin America (Figure 6.15). The deployment of urban RTSPV depends on various factors, including the competition with other low-carbon generation options outside cities. In the case of the United States, for example, solar PV in total meets 14% of urban electricity needs, but around half of it is generated through rooftop or utility-scale PV outside cities.

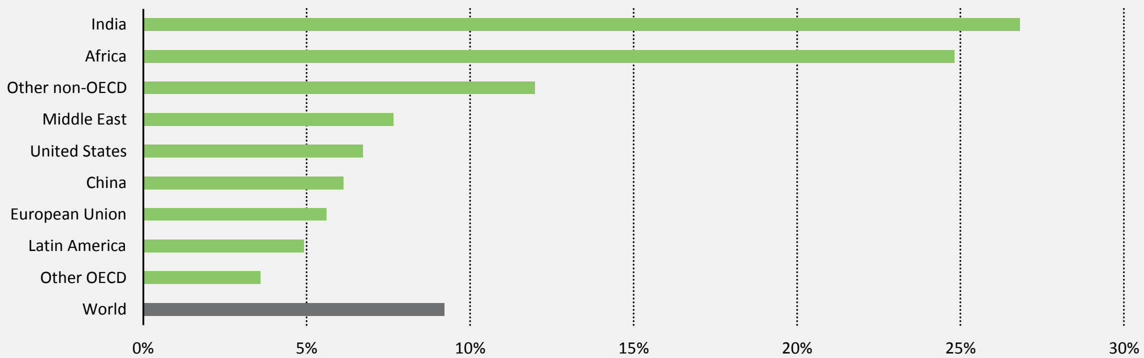
Figure 6.14 Global urban final energy demand by fuel in the 2DS



Source: IEA analysis and IEA (2015b), *IEA World Energy Statistics and Balances* (database), www.iea.org/statistics.

Key point *In cities, electricity is the second-largest final energy source after oil and has the potential to become the largest source after 2030.*

Figure 6.15 Share of urban final electricity demand met by rooftop PV in cities, 2050

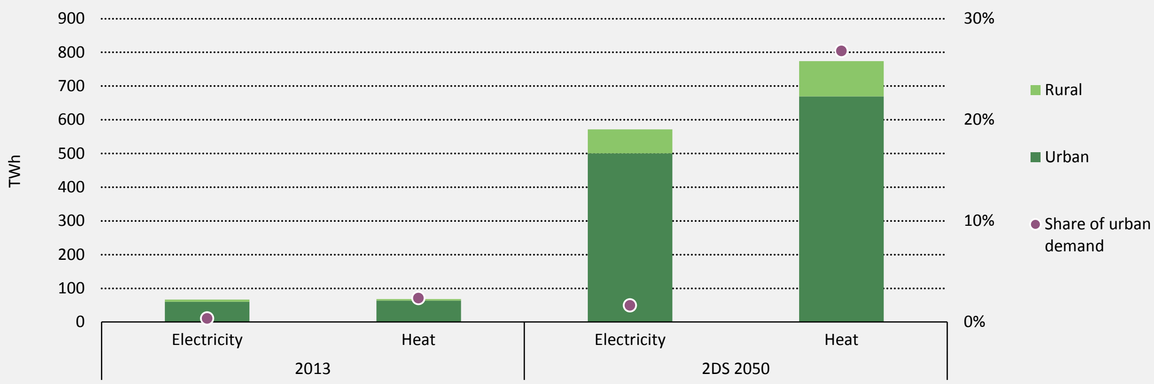


Key point *The share of urban RTSPV varies across regions, depending on local resource conditions, but also on competition with alternative generation options to meet urban electricity needs.*

WTE in cities

The contribution of MSW to urban energy needs on a global level is limited today, covering in 2013 an estimated 0.4% of electricity and 2% of district heating in cities. In the 2DS, absolute electricity and heat generation could increase for electricity eightfold to 580 TWh and for heat even by a factor of eleven to 775 TWh. WTE plants would still cover only 2% of urban electricity needs in 2050, but on the heat side, MSW in co-generation and heat plants could provide 27% of global district heating demand in cities (Figure 6.16).

Figure 6.16 Global urban electricity and district heat generation from MSW



Source: IEA analysis and IEA (2015b), *IEA World Energy Statistics and Balances* (database), www.iea.org/statistics.

Key point *Heat from MSW used in co-generation and heat plants could cover almost 30% of global district heating demand in cities.*

CO_2 reductions and energy savings

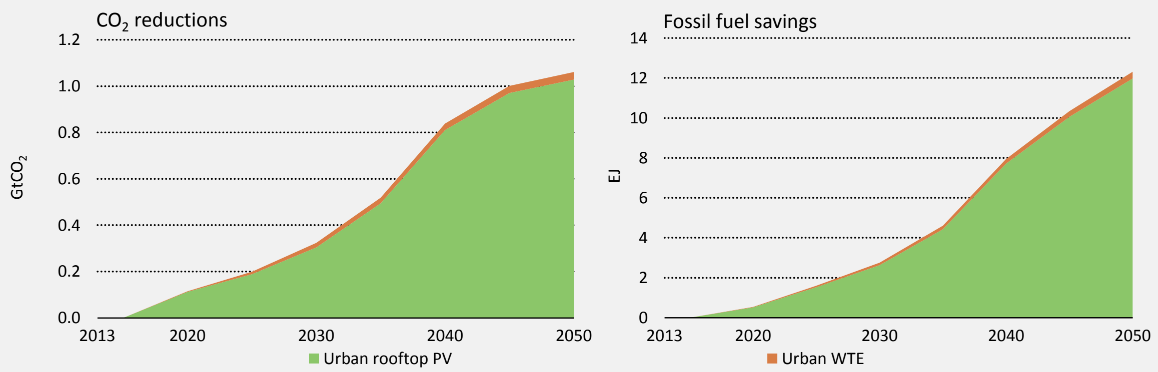
The incremental deployment of RTSPV in cities contributes to the cumulative reductions in carbon dioxide (CO_2) linked to urban electricity consumption. In the 2DS, these cumulative reductions amount to 18 gigatonnes of carbon dioxide ($GtCO_2$) or 9% of the emissions reduction, when compared to the 4DS (in comparison to the 6DS, CO_2 reductions of 22 $GtCO_2$ or 8% of the total cumulative reductions between the 2DS and 6DS) (Figure 6.17). Related annual fossil fuel savings total around 12 EJ in 2050 in the 2DS in comparison to the 4DS (13 EJ relative to the 6DS), an amount slightly lower than the total primary energy demand of France in 2013. On a cumulative basis, almost 172 EJ of fossil fuels are saved through RTSPV in cities between 2013 and 2050 (again relative to the 4DS). When compared to the 6DS, the fossil fuel savings increase to around 205 EJ.

The corresponding contributions from WTE are much smaller. Cumulative CO_2 reductions amount to 0.8 $GtCO_2$ or 0.4% of the reductions in CO_2 linked to urban electricity consumption between the 4DS and the 2DS.[31] Using MSW for urban electricity and district heat generation results in cumulative fossil fuel savings of 7 EJ in the 2DS (relative to the 4DS).

Defining resilience of cities and quantifying indicators to measure it are difficult tasks. Still, comparing the share of locally generated electricity generation with the electricity consumed in the residential and services sectors (the two sectors being most vital in an emergency situation for providing essential needs to the cities) can give some idea of how much essential electricity needs can be met by local sources. In 2050, in the 2DS, urban RTSPV alone provides 18% of these electricity needs. When electricity from MSW is added, the percentage increases to 22%.

31 The smaller contribution of WTE compared to RTSPV is not only caused by the lower deployment, but also by the fact that MSW is not necessarily a carbon-free fuel, but its carbon content depends on its composition. Here a conservative assumption has been made that half of the MSW is non-renewable, reflecting the current situation in many countries today and resulting in an assumed CO_2 emission factor of 50 $kgCO_2/GJ$.

Figure 6.17 CO_2 reductions and fossil energy savings from urban RTSPV and WTE in the 2DS relative to the 4DS



Key point *Deployment of RTSPV in cities provides around 8% of the cumulative CO_2 reductions linked to urban electricity consumption in the 2DS, corresponding to 9% in cumulative fossil fuel savings.*

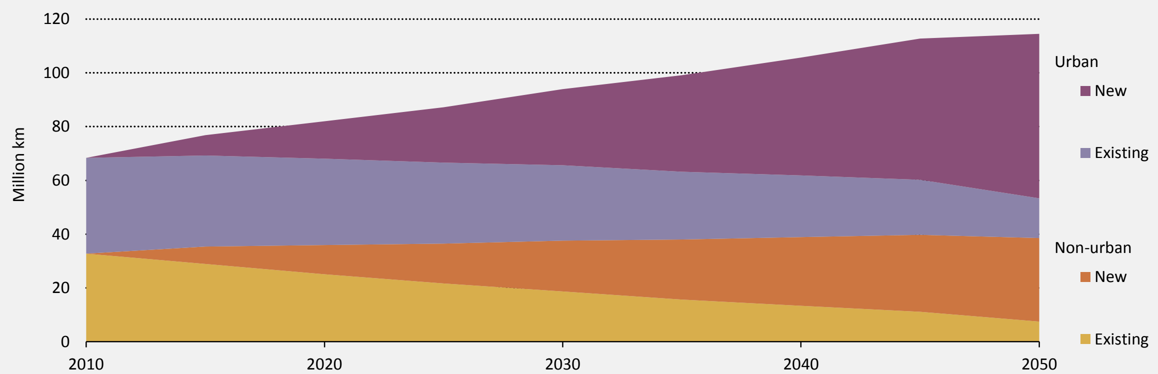
Smarter urban energy networks

Beyond technical options for electricity and heat generation, a critical issue for cities is the effective distribution of energy to end users. The planning and operation of urban energy distribution networks will be crucial to ensuring that the potential for distributed energy resources and heat options becomes a viable economic reality. The role of networks is already fundamental today. Power grids in urban areas make up over 80% of the total electricity system network length (NRGExpert, 2014). District heating networks remain largely an urban phenomenon because heat cannot be economically transported over large distances. Urban networks to deliver natural gas to homes for heating and cooking are a common feature in cities in cold climates.

A very large percentage of all electricity demand and, as analysis earlier in this chapter shows, a sizeable portion of renewable generation, will be connected to urban distribution networks. The resulting size and complexity of most urban grids means that under the 2DS, electricity distribution network investments will have to make up between 65% and more than 80% of all the network investments to 2050 depending on the region. Investment in district heating networks themselves will make up around a quarter of the *total* cost of district heating (i.e. the levelised cost per unit energy delivered).

The crucial role of urban distribution networks reinforces the need to fully understand their potential and all possible constraints so as to make sustainable energy planning more effective. Distribution grids face issues in incentivising investment and recovering costs under a 6DS, business-as-usual trajectory. Integrating both the increases in distributed energy resources and the increasing participation of the demand-side poses particular challenges. These challenges will require radically improved monitoring, control and planning of urban energy networks, and coupling with other energy sectors (e.g. heat or transport). Both requirements increase the challenge in allocating investment and recovering costs. The investment needed to establish and maintain a distribution network will remain significant (Figure 6.18). However, the planning and operation of electricity systems can be optimised through the joint planning and operation of infrastructure, the management of demand, the increase of observability of energy flows through upgraded information technology infrastructure, and the use of emerging distributed energy resources.

Figure 6.18 Urban and non-urban distribution infrastructure



Key point *Distribution grids in urban areas dominate power network investments.*

Developments at the distributed level do not mean that the transmission grid should be ignored. In fact, the interface between getting energy to urban areas (transmission) and delivering within urban confines (distribution) in both planning and operation is a significant challenge of co-ordination and regulation across networks and for other energy or infrastructure technologies.

Historically, and still today in many regions, single entities within vertically integrated monopolies were responsible for the operation and planning of transmission and distribution systems. Through the 1990s and 2000s, many power systems experienced a restructuring, whereby the operation and planning of transmission and distribution were transferred to individual owners and operators. Physically, no change occurred: power flowed from centralised power plants, voltages were scaled down at different levels through transformers and substations, and electricity was ultimately distributed to customers as a unidirectional flow of power. Changes have been institutional; independent operators of networks and centralised markets have been created to allocate energy, capacity and ancillary services.

The transformation of urban energy systems towards sustainability has been led by a penetration of distributed energy resources (DG including solar PV, electrified transport and heat, energy storage and more controllable demands). In this context, boundaries between urban energy distribution systems and national systems will become less defined, and will be amenable to regulatory, policy and economic re-appraisal. The debate over how to integrate distributed energy resources is evolving and system-specific. Issues involve choosing a market and regulatory design, system architecture and technical solutions to provide the highest security, quality of energy service delivery and environmental benefits at the lowest cost. Regardless of the particular architecture or regulatory structure, distribution grids and cities are evolving towards energy hubs that will require new, smarter ways to plan and operate energy networks across different energy carriers.

Smarter distribution grids

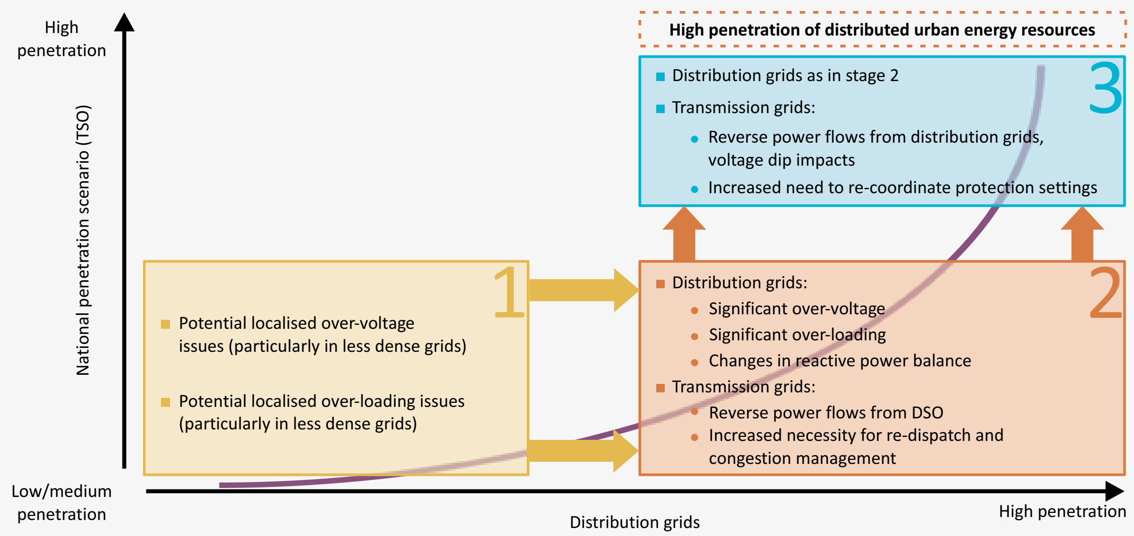
In the past, utilities planned urban distribution system investments primarily on the basis of projected load growth and required replacement of equipment. The ability to manage demand and power flows in real time was limited. The increasing penetration of PV and other distributed energy resources has multiplied both the opportunities and the challenges. This point may be illustrated by considering the issue of increasing DG penetration from the perspective of the owner or operator of a power distribution grid, taking RTSPV as an example (Figure 6.19). As the penetration of PV and other DG options increases, three stages of development can be clearly differentiated, depending on the relative impacts on both urban distribution grids and the transmission grid beyond a city.

Stage 1: Low to medium DG penetration occurs in local areas. Local consumption exceeds generation, and distribution of power is uni-directional. A small number of circuits, predominantly in less dense areas, show reverse power flows when generation exceeds demand (i.e. in times of high solar irradiation).

Stage 2: High DG penetration occurs in selected areas within the city. Local generation in a few areas exceeds local consumption, and grids are increasingly bi-directional. Reverse power flows from the distribution system to the transmission system can be observed frequently. Within these distribution grids having high PV penetration, the installed PV capacity exceeds the local peak load many times over, leading to potentially very significant overvoltage and overloading issues. Investing in increasing the hosting capacity of a network becomes necessary. In parallel, in individual hotspots with a high PV penetration, the impacts can feed further upstream. Reverse power flows, from the distribution grid into the transmission grids, can cause issues at the system level, including the re-dispatching of conventional power plants. These issues increase the need for reserves and for revising procedures for managing network congestion.

Stage 3: High DG penetration occurs throughout a city. Urban energy networks frequently generate reverse upstream power flows, with a significant impact on transmission grids. The focus shifts on operation at higher levels, as distributed networks are now required to provide a degree of system security and ancillary services. Technical solutions are required for grid integration of DG resources to accommodate power quality issues at very high voltage levels, affecting network properties necessary to maintain stability.

Figure 6.19 **Three stages of penetration of distributed energy resources and impacts on urban distribution and national transmission systems**



Notes: TSO = transmission system operator; DSO = distribution system operator.
Source: IEA analysis based on IEA-PVPS (2014).

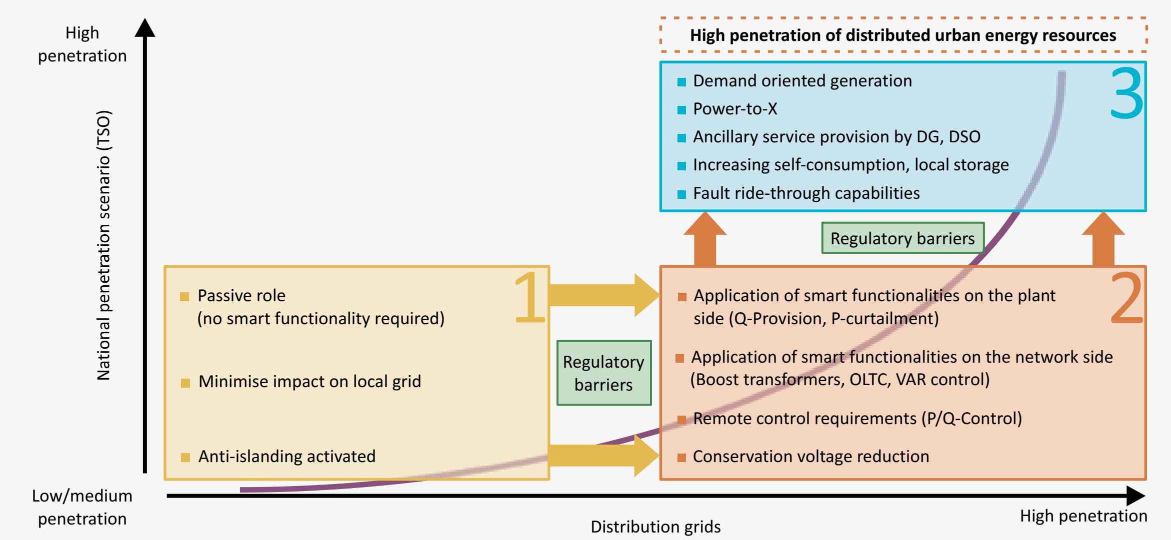
Key point *Increasing penetration of distributed urban energy resources has escalating impacts on the overall system.*

The technical and economic challenges associated with this transition process include both local and systemic (national-scale) issues. Local challenges of high PV penetration scenarios affect urban distribution systems, whereas systemic challenges affect the operation and stability of the national transmission system. Both perspectives have to be addressed through planning, deployment, demonstration and research of technical solutions that will support active distribution networks with a high penetration of distributed energy resources.

The increase of variable renewables connected to urban grids, the overall level of electrification, and the electrification of heat and transport imply that distribution systems have to become (and are already becoming in areas with high penetration of these technologies) semi-autonomous entities with their own balancing of variable generation. Distribution systems must also exercise their own control over dynamic and flexible load across different sectors (heating, transport), accommodate two-way power flows from DG and storage; and manage new forms of interaction and control both at the DSO level and the TSO level. Some observers call these transformed systems "active distribution networks". Such networks are enabled by new instrumentation and control channels at various levels.

A suite of options exists to transform current distribution grids into active distribution networks to cope with the high penetration of DG and unleash the flexibility potential in cities. The exact economics of each option varies system by system, but the increasing penetration of distributed resources may be considered in three stages (Figure 6.20).

Figure 6.20 **Three stages of penetration of distributed energy resources: Strategies towards active distribution networks**



Notes: OLTC = on-load tap changers; Volt-Ampere reactive.
Source: IEA analysis based on IEA-PVPS (2014).

Key point *Increasing penetration of DG calls for a holistic planning at the levels of equipment, distribution network and the larger system.*

- **Smart DG: Making distributed energy resources part of the solution.**
DG resources in cities, like those further upstream, should provide their own set of technical services, bear part of the responsibility for providing reliability and security, and facilitate their own integration at low cost. These responsibilities include provision of reactive power and system services, or allowing the distribution grid operator to control power output or other properties of the equipment. In the past, insufficient integration practices have led to inefficient economic and regulatory adaptations. The causes generally involve poor long-term planning to scale up distributed energy – exemplified by the large-scale retrofitting process prompted in Germany in 2011. Design, planning and regulatory activities should take these technical capabilities proactively into consideration.

  In particular, smart inverters in PV systems in dense urban areas can provide voltage and reactive power support to local distribution feeders. Under the right technical and regulatory framework, smart inverters can also provide flexibility to system operators further upstream and balance the larger system. Wind turbines on distribution networks in peri-urban areas, equipped with active and reactive power support, can also provide services to system operators and contribute to their own integration.

  On the other hand, increasing the amount of energy consumed on-site reduces the impact that distributed energy resources have on the broader energy system. These solutions can be less technical and more driven by incentives, i.e. through business models that turn consumers into producers and prosumers. A full treatment of prosumption is beyond the scope of the analysis, but flexibility on the demand side could help optimise the profile of energy drawn from the larger system by better matching demand with generation. The use of on-site storage or demand-side management could further increase the positive impact and is explored further below.

- **Smart planning, operation and investment in physical assets for distribution system operators.** Given the increasing density and variety of power sinks and sources connected to urban distribution networks, better planning and operation can proactively shape a power system by exploiting the properties of a large number of distributed energy resources. Emerging cases show the importance of modelling and analysing the ability of the distribution system to host distributed energy resources, the optimal location for these resources, and the opportunity to reduce or delay "classical" investment in physical network infrastructure. DSOs are increasingly modelling distribution systems similarly to how bulk-power/transmission systems are modelled. Specifically, advanced modeling includes high-resolution representation of DG resources, new approaches to demand forecasting that account for both controllable and non-controllable loads, and the inclusion of multiple types of end-user load profiles (for example, a home with an EV).

  The most significant technology area, where investment is growing at a 180% compound annual growth rate (IEA, 2015e), is information and communication technologies (ICT) and supervisory control and data acquisition (SCADA) systems at the DSO level (Table 6.3). These technologies increase the *observability* of the network, i.e. to monitor voltages and power flows along distribution feeders. They also allow the management of two-way physical flows of power. In the past, such levels of observability were unnecessary for passive loads in distribution networks. Dynamic monitoring and control can allow the adjustment of distribution networks in real time in ways that were previously uneconomical – for instance through OLTCs or step voltage regulators (SVRs), technologies allowing the automated regulation of voltage levels.

Table 6.3 Generic "smart" technology options available to operators of distribution networks

DSO resource	Cost/benefit reported as	Role/description	Indicative benefit/cost ratios where positive
SCADA systems, improved monitoring and forecasting, upstream flow of information	Smart planning and operation	Improves the observability of the network, hosting of non-dispatchable generation.	1.1-3.3
Automatic Network Reconfiguration	Smart planning and operation	Besides increasing the voltage and current related hosting capacity of distribution grids, reduction of network losses could be within the scope of automatic feeder reconfiguration.	1.1-2.2
On-Load Tap Changer	DSO smart assets	Allows the automated regulation of voltage by changing the transformer winding ratio, either remotely or autonomously.	1.2-1.8
Boost transformer	DSO smart assets	Used to stabilise the voltage along heavily loaded branch feeders. Usually, booster-transformers are used in long feeders with dispersed consumers to boost the voltage under heavy load conditions.	1.5-2.1
DSO VAR control	DSO smart assets	With more distributed energy resources changing active/reactive power balance, fast-acting power electronic devices on the distribution grid side can stabilise grids, such as Static VAR Compensators (SVC). Mitigates voltage raises and/or compensates reactive power by injection of reactive currents.	1.1-1.9
Conservation Voltage Reduction (Smart DSO)	DSO smart assets	ICT solutions that enable distribution feeders to be operated at the lower end of the voltage range as required for system reliability. Turns DG into flexible resource, reducing the need for investments in new generation resources.	1.1-2.6
Distributed storage	DSO storage	Storage at the distribution grid level provides peak shaving, load levelling, power quality services and can be used as a back-up solution for frequency.	1.1-2.4

Realising the potential of smart technologies for urban distribution networks requires developing operational strategies for hosting distributed energy resources. Choosing an adequate set of smart technologies involves a balance of rule-of-thumb screening (the current widespread option) and more sophisticated cost-benefit analyses – the methodologies and results of which vary greatly system to system. Beyond conventional grid reinforcement techniques, additional or modified equipment and communication between network devices, power plants and network operators are needed to increase operational flexibility.

- **Advanced metering infrastructure (AMI), demand response and cross-sectoral integration of urban energy networks.** Implementation of AMI can lead to significant changes in how energy resources are planned and operated locally and nationally. In early stages and at a local level, locally generated energy can be used to meet local loads. In this context, storage systems or manageable loads controlled by sophisticated energy management systems can be used to ensure uptake by consumers, by increasing the market signals and mechanisms on a local and national level. In later stages, the same local energy management system can be integrated in a central management system to receive signals (prices or activation). The local energy management system will decide whether the locally generated energy is used to meet domestic loads or whether it should be sold to the market or a system operator via a virtual power plant arrangement. This decision requires reliable forecasting and planning capabilities by the distribution network operator and new market signals.

These three strategies are non-exclusive, but rather should be deployed in parallel and require a system perspective with clarity on the planned development of assets within the power system and the penetration of technologies in all demand sectors.

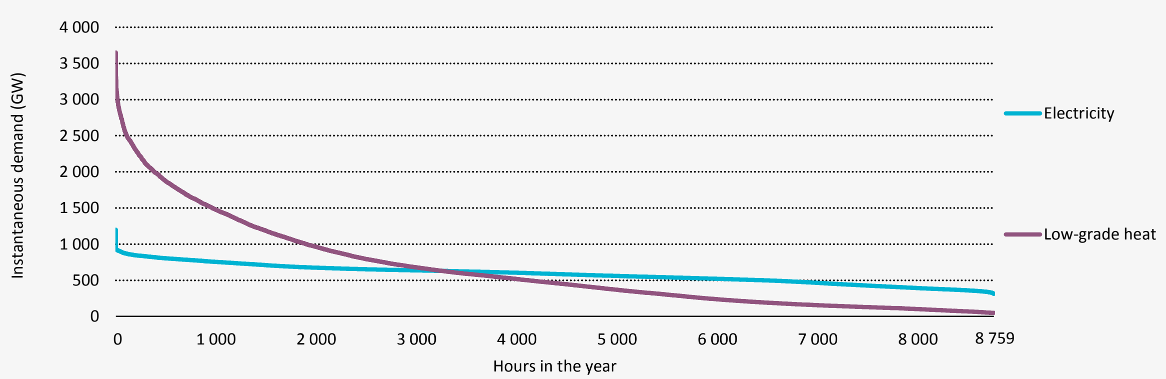
The analysis of the costs and benefits of different strategies for transforming urban energy networks needs to be done on a case-by-case basis. Of all options, evidence shows urban AMI/DR and improved smarter planning and operation from the DSO side yield the highest net benefits. Because of the significance to the urban context, demand response within urban areas from power-to-heat is presented in further detail.

Power-to-heat

Power-to-heat refers to the conversion of potential surplus electricity from renewables to other applications as heat energy carriers. This conversion exploits the low utilisation of heat-generating and heat-storing equipment close to the end consumer. The issue can be best illustrated using a load duration curve. A load duration curve portrays a given demand (electricity, heat) over a long period – typically one year. Normally, demand is shown over time (a "chronological" load curve). In load duration curves, demand is reordered according to the level of demand. The hour with the highest demand comes first, and then the second-highest and so on until all data are ordered in descending order. A similar load curve can be developed for the amount of electrical load that requires a flexible response (i.e. the load net of intermittent renewables), to gain an appreciation of the annual variation.

Load curves for electricity and heat have been plotted in Figure 6.21 for the European Union, for the year 2030, and accounting for all sources of space heating provision amenable to power-to-heat strategies. Over a year, a significant disparity exists in the utilisation of heating and electricity systems. A complete electrification of heat demand would require significant increases in capacity and flexibility (and thus reduced seasonal utilisation) of the power fleet. Conversely, a large potential exists for increasing the flexibility of electricity systems in the 2DS.

Figure 6.21 Load curves for electricity and heat in the European Union, 2030

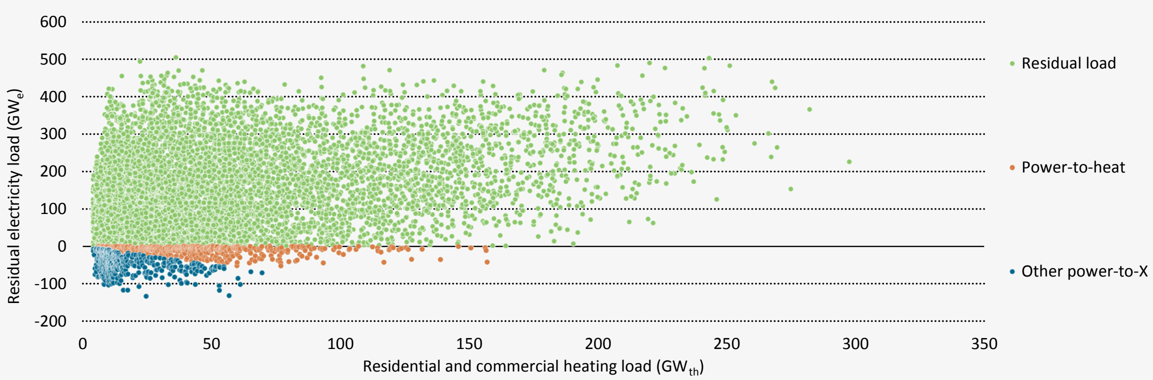


Key point *Demand for space heating and electricity have significantly different daily and seasonal variations.*

To determine the potential effect of heating technologies on supply-side flexibility, dispatch optimisations were soft-linked to the IEA's scenario modelling. For a technically sound use of a power-to-heat service, negative residual load (e.g. when variable renewable energy [VRE] electricity generation exceeds electricity demand) has to occur simultaneously with heat demand, whether it be centralised or decentralised. One way of highlighting this is by plotting the residual load (net) load against the demand for heat in every hour of a given year.

In Figure 6.22, each point represents one hour of the year 2030 with the corresponding space heat demand and the residual load. The orange and blue points represent hours of the year in which negative residual load (i.e. otherwise curtailed power where the system is not flexible enough to accommodate variability) and heat demand occur simultaneously. Orange points depict moments in the year in which the heating load is higher than the (negative) net load – meaning for some hours, this overabundance of electricity production can be, technically, fully taken up by generating heat. Blue points represent moments in a given year when overabundant power production exceeds heat demand, which implies further flexibility is required. This flexibility could be accomplished through distributed heat storage (i.e. hot water immersion heaters or storage-enabled heat pumps). At the larger scale, flexibility could be provided by heat accumulators in district heating networks (Box 6.4) or through additional measures to utilise excess electricity production.

Figure 6.22 **Load net of intermittent generation versus heat demand in the European Union, 2050**



Note: GW_e = gigawatt electrical capacity; GW_{th} = gigawatt thermal capacity.

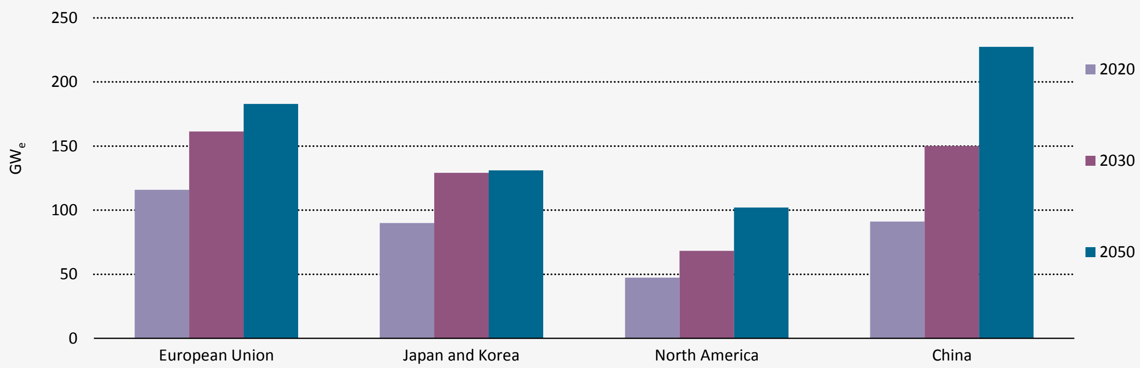
Key point *For power-to-X, negative residual load has to occur simultaneously with flexible demand.*

The combined generation of heat and power in co-generation plants can be exploited to link electricity and heat systems. Extraction-condensing co-generation technologies are able to regulate electricity and heat production; more importantly, where coupled to a district heating network, the thermal mass of the network or large hot water storage accumulators can be employed to increase the flexibility of the provision of heat and electricity (Box 6.4). Such flexibility can, in turn, be used to provide balancing and other system services either locally to support integration of distributed energy resources, or to the larger system to balance variable renewable generation.

Beyond co-generation and district heating, on-site heat storage can be enabled to respond to system signals. Electric heat pumps are a key technology for decarbonising buildings; its output in the 2DS increases to 9.2 EJ by 2050.

Analysis of 2DS results reveals a significant potential of, respectively, 89 GW and 142 GW that could be provided by power-to-heat in the 2DS by 2050 (Figure 6.24). China has the highest potential, given the high heat demand densities and penetration of district heating in northern China and the significant potential for heat pump heating in the "Transition" regions – a densely populated belt across central China. The scale-up also reflects the differing infrastructure growth patterns in non-OECD countries, where much of the infrastructure remains to be built.

Figure 6.23 Power-to-heat potential in four key regions in the 2DS



Key point *The low-cost resource provided by assets in the space heating with low utilisation makes power-to-heat an attractive option for providing flexibility to the power sector in the 2DS*

Box 6.4 Smart energy networks at multiple scales: Emerging examples

Denmark has one of the highest penetrations of intermittent renewable energy in the world. The country has also undergone a transition over the last several decades from a dependence on large central generators to smaller decentralised systems, relying heavily on DG, microgrid control and cross-sectoral integration. The country is an excellent example of measures taken with a view across the local and national scales of the system.

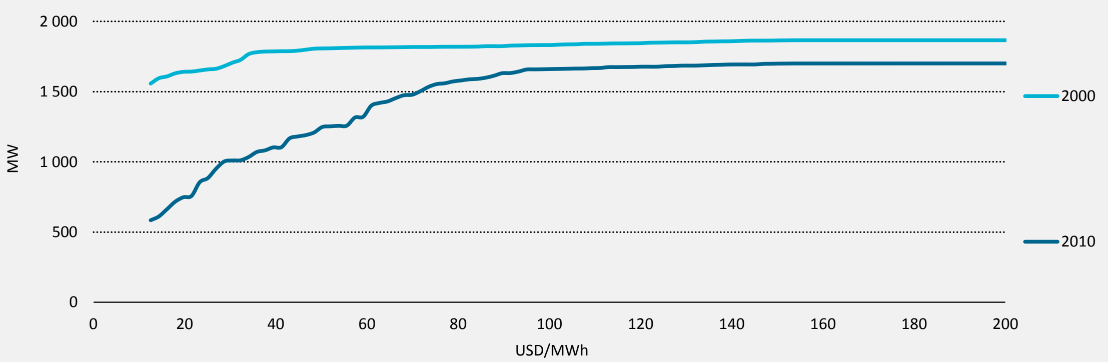
Denmark has one of the highest rates of distributed energy use, generating over 60% of its electrical energy and about 80% of its district heating needs from co-generation systems. The 1979 Heat Supply Act was passed in response to the oil crises in the 1970s. The act first required local authorities to provide data on useful heat usage, existing technology infrastructure and final energy consumed for heat (van der Vleuten and Raven, 2006). A second phase required counties (the next level of geographical aggregation) to prepare "regional summaries", which led to "regional heat plans". The plans specifically required prioritisation of heating supply options and locations for heat supply technologies and heat distribution networks.

The regional plans subsequently set the vision for municipal and district energy network planning. The municipalities engaged with the local energy utilities and jointly prepared municipal heat plans, designed within the confines of the regional plan. The third phase involved expansion of co-generation, heating and gas infrastructure, which was co-ordinated by local authorities (municipalities) to ensure coherence with both regional and municipal plans. Extensive utilisation of co-generation has contributed to Denmark achieving approximately 39% annual wind energy contribution. About half of the fuel for co-generation systems comes from renewable or waste sources.

This decentralisation allowed Denmark to increase power system resiliency while also reducing dependence on imported oil, increasing energy productivity and providing increased system flexibility. Recent regulatory changes in Denmark made it possible for co-generation plants to sell produced electricity in the power market, leading to positive synergies between heat and electricity. During periods of high electricity prices arising from low wind power availability, co-generation plants feed electricity into the grid and store heat in large storages or in the heat networks themselves.

Conversely, during periods of surplus wind generation (resulting in depressed electricity prices), output from co-generation plants is lowered, and heat demand is serviced from the stored capacity. High-capacity direct electric boilers provide additional capacity to make use of the low-carbon, low-price electricity. The effect is shown in Figure 6.25, where the flat price duration curve seen in 2005 (i.e. heat and power generation not responsive to the system) has been replaced with a curve sensitive to changes in the generating plant mix at any point in time.

Figure 6.24 **Power price duration curve for co-generation plants in Denmark, before and after opening up DR to market signals**



Source: Energynet.dk (2016), *Download of Market Data.*

Key point *Opening DG in urban networks to market signals can release significant amounts of flexibility.*

Towards cities as microgrids, urban energy islands and virtual power plants

Distribution network operators in urban areas typically manage changes in loads by sourcing more or less power from the broader system. A national system will thus have to maintain generation capacity to meet changes in load from an urban area, whether through market mechanisms or regulated entities. Cities, hotspots of distributed energy resource penetration, and other demonstrations show that co-ordinating distributed energy resources within a local area can reduce the need for investment in the larger system and the requirements on reserve capacity to ensure reliability within a territory.

However, many of the technical options are untested at the distributed scale. As distributed resources penetrate further, and end users and cities become more autonomous consumers of energy, the exact balance of how reliability is ensured at different levels of the system can be expected to evolve. The role of distributed energy resources in providing system adequacy and reliability can be typified in grid codes, and the regulatory aspects are crucial. As the performance characteristics and capabilities of distributed energy resources and microgrids change, so does the structure of contracts and tariffs, which determines when and to whom these resources will be available. Increased co-ordination at the physical boundaries of urban infrastructure will be required.

"Smart substation" demonstrations are highlighting these possibilities. In co-ordination with distribution and transmission system operators, the French RTE "smart substation" project is building and operating two fully "smart" substations at the system boundary between the local urban area and the national network. The project will provide a fully digital interface and exchange of information between the local and national operators. Other examples include clarifying management protocols for substations at these system interfaces, or ensuring that territories and distributed energy resources providing reliability to the overall system are not called simultaneously by different operators or other commercial entities, or that dispatching of DG does not affect local distribution systems.

However, beyond better co-ordination between cities and national operators, technology innovation has the potential to alter how cities and isolated grids interact with the rest of the system, in the form of microgrid architectures and cities as virtual power plants (VPPs). Microgrids are localised grids that can disconnect from the traditional grid to operate autonomously and help mitigate grid disturbances to strengthen grid resilience. Even where they lack the physical architecture and islanding capabilities of microgrids, neighbourhoods or cities acting as VPPs can combine a rich diversity of independent resources into a network via sophisticated planning, scheduling and bidding through ICT-enabled smart technologies. Regional VPP demonstrations have been created in France (Nice Grid), Canada (PowerShift Atlantic) and the United States (NY Consolidated Power Edison).

These technology options represent a further evolution in the decentralisation of energy resource provision for urban areas. In the past, urban microgrids were quite rare, and cost and complexity limited them to high-priority sites. In transforming power systems, microgrids are becoming more common due to rapid cost declines and new business models such as "microgrids as a service."

The potential energy generation located within microgrids can be utilised to mitigate the impacts of large-scale grid outages on the microgrids' critical functions. Military installations, research laboratories, data centres and banks often have backup power systems so that their operations are not affected by commercial grid outages. Until recently, many of these backup power systems were individual diesel generators utilised only during emergencies. However, advanced microgrids are now being utilised in many cases to provide cost savings when the grid is available and resiliency when it is not.

Decentralised generation, virtual power plants and localised microgrids can be deployed to increase the reliability and resiliency of the broader system. By providing redundancy, a large number of smaller distributed systems mitigates the impact of a failure of one single component (i.e. a large generation unit or a power line), and allows the system to be reconfigured more easily to face disruptions. Decentralised systems have also been shown to increase resiliency from attacks or natural disasters (Bower et al., 2014; Maitra et al., 2014), and can be used to recover from outages more efficiently. Territories acting as microgrids can provide resources to capacity markets, demand response and ancillary services.

Recommended actions for the near term

Local clean energy sources in cities can provide local and national benefits. On a local level, benefits include reduced air pollution, fuel cost savings for end users and resilience against disruptions; on a national level, benefits include energy security, reduced investment needs and GHG reduction. To exploit the potential of local energy supplies, comprehensive measures are required that mobilise swift actions across different policy levels and involve stakeholders from government, industry, research and the public.

On a national level, many countries already pursue policies that foster the use of clean energy sources and technologies. National policies (such as the removal of energy price subsidies, legally binding GHG emissions reduction targets, stable and internationally co-ordinated carbon-pricing mechanisms) could incentivise urban uptake of clean technology options such as IEH and RTSPV. For IEH in particular, taking advantage of cost-effective opportunities for IEH recovery in industrial sites requires a detailed assessment of their process performance and integration level, including pinch analysis as part of energy management systems. Improved process integration of industrial sites would then open opportunities for further sustainable benefits through exports to local thermal networks and/or IEH-based electricity generation.

Energy research, development and demonstration is a further policy domain where national policy makers can support technologies needed in the urban energy context. Research activities to reduce the costs of battery storage can facilitate the integration of RTSPV into the electricity system, either on-site or at the distribution network level. For excess heat recovery, government/industry research collaboration is needed to increase technical recovery heat potentials and improve their economic viability. For WTE technologies, improvements can be achieved through the increase of electrical efficiencies and increased heat utilisation. Major challenges are the heterogeneous nature of waste, low heating value and corrosion in boilers. Although the technology for waste gasification with gas cleaning has been demonstrated, more experience is needed in its long-term operation.

While these policy efforts on a national level are not specifically targeted towards the implementation of clean generation or energy recovery technologies on a local level, they are often a pre-condition, whether the local environment is urban or rural. National policies alone, however, are often not sufficient; they need to be complemented by measures on the city level. These local policy actions may be needed to address the implementation of clean technologies in the urban context or for the integration of the urban energy options in the regional or national energy system. To raise the awareness for solar PV or solar thermal water heating among homeowners, cities can develop detailed solar maps for all urban buildings, with information on solar yields, installation costs and possible cost savings. Similarly, for heating and cooling, mapping of demand and source points can help to identify cost-effective opportunities for excess heat recovery. Tracking implementation levels of recovered excess heat in official energy statistics would complement these assessments.

The actual deployment of these decentralised technology options at the urban level hinges on their economic viability. Often, due to smaller unit sizes, decentralised technologies suffer from higher specific investment costs compared with large-scale, centralised units. For some technologies, such as RTSPV, the main strategy for reaching cost-competitiveness may involve national policies, such as technology-specific support policies and carbon pricing, that will bring increased deployment and thus expected future cost reductions. For other urban technology options, additional revenue streams are needed. As shown in Figure 6.7, the economics of WTE plants can be improved through gate fees and DHC sales. While feeding electricity into the grid is possible in most deregulated and many regulated electricity markets, heat (or cooling) exports into the district energy system are so far possible in only a few countries/cities. One example is Stockholm, where the energy company Fortum Värme offers long-term and transparent terms for trade in excess heat and surplus capacity in heating and cooling systems (Open District Heating, 2015).

Linking the broad diversity of urban energy demands with the significant potential for distributed urban energy resources requires advanced energy distribution networks. Mitigating the impact on the grid of DG can exploit synergies with other sectors. Tapping assets with low utilisation in other sectors, such as residential and commercial heating supply, can provide flexibility at low cost. As cities move towards more renewable and distributed energy provision and the electrification of transport and thermal comfort demands, the planning and operation of urban energy networks need to evolve. Technical solutions with high benefit-to-cost ratios exist, but policies must be adapted early on to be able to fully exploit these solutions. National governments and cities should explore regulatory changes and lessons learned from jurisdictions where microgrids, VPPs and other forms of aggregation of distributed resources are being piloted and increasingly deployed at a larger scale to deliver low-cost integration of renewable and sustainable urban energy supply.

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Chapter 7

Policy and Finance Mechanisms for Urban Areas

Ambitious policy action in urban areas is crucial if the world is to move to a sustainable energy pathway. The commitment of all levels of government, working in a co-ordinated manner, is needed to enact innovative and effective policies, and to provide the right conditions to attract investment.

Key findings

- **Urban areas are at the heart of the sustainable energy transition.** *As more and more people live and work in urban areas, so the decisions made by policy makers become ever more important. Spatial planning decisions, transport infrastructure developments and building projects have long-lasting impacts on urban energy consumption.*
- **To ensure that policy decisions achieve sustainable development objectives in a cost-effective way, local, regional and national governments must work together across vertically and horizontally integrated policy frameworks in which targets, policies and implementation are aligned.** *Each level of government needs to co-ordinate its powers and involvement with other levels to increase innovation, action and effectiveness.*
- **National policy makers can support cities by setting policy frameworks that provide strong direction and co-ordination among the different layers of government to align policies in a way that supports the energy transition.** *In some cases, the devolution of more powers to local levels, within an integrated policy framework, can enable more effective action.*
- **Cities, municipalities and local governments are essential implementers and enforcers of national policies;** *they are also policy innovators where their powers allow. Even with only the most basic planning powers and service delivery roles, urban governments can still make plans and policies that affect urban energy consumption.*
- **To harness urban sustainable energy potential, policies and actions must ensure that existing municipal planning, service delivery and other functions work together** *to improve system-scale energy efficiency while minimising greenhouse gas (GHG) emissions and other environmental, social and health impacts.*
- **While financing and business models exist to service current municipal needs, these models need to adapt to different contexts** *and take into account technological improvements and opportunities.*
- **As ambition increases, financing will need to scale up.** *This step requires further co-ordination among governments to increase the role of private financing by improving investor confidence and the business case for these investments.*

- **The urban energy transition requires skills, innovation and information sharing so that successful approaches can be built open.** *National governments can assist in this process, for example by building capacity, rewarding innovation and promoting exchanges of lessons learned.*

Opportunities for policy action

- *A large part of the sustainable energy potential offered by cities will remain untapped in a business-as-usual scenario; therefore unlocking the so-called "policy potential" is as important.*
- *National governments need to develop governance frameworks that enable cities to lead, implement and partner on solutions that reduce GHG emissions. This includes allocating fiscal and legislative powers where appropriate, encouraging capacity development, collecting data, and reporting on energy and GHG emissions.*
- *Cities need to integrate energy objectives within the core functions of city planning, service delivery, procurement, maintenance and information provision. This requires incremental but ambitious shifts to providing services and enhancing liveability within a carbon-constrained world.*
- *Capacity building and financial assistance are crucial for cities in non-OECD countries; therefore national governments, multilateral development banks, NGOs and international organisations have strategic roles to play.*
- *The role of governments in OECD member countries is to enable cities to successfully pioneer new financial mechanisms and governance approaches and to provide examples of best practices to emerging economies.*
- *All governments need to introduce policies that create an enabling environment to identify and implement solutions based on local circumstances. Building linkages among citizens, community associations, different levels of government, developers, utilities, transport authorities and businesses will happen only with government leadership.*
- *All levels of government will be responsible for leveraging private-sector ideas, expertise and financing to identify and invest in low-carbon solutions. It is critical to improve investor confidence, identify opportunities to reduce GHGs cost effectively, and strengthen new business models for commercial involvement.*
- *No single template for successful policies exists but solutions are possible. Multiple levels of governance need to be effectively co-ordinated, with the right governance, policies and incentives to enable cities, the private sector and citizens to pursue strategies to lower carbon emissions with increasing ambition.*

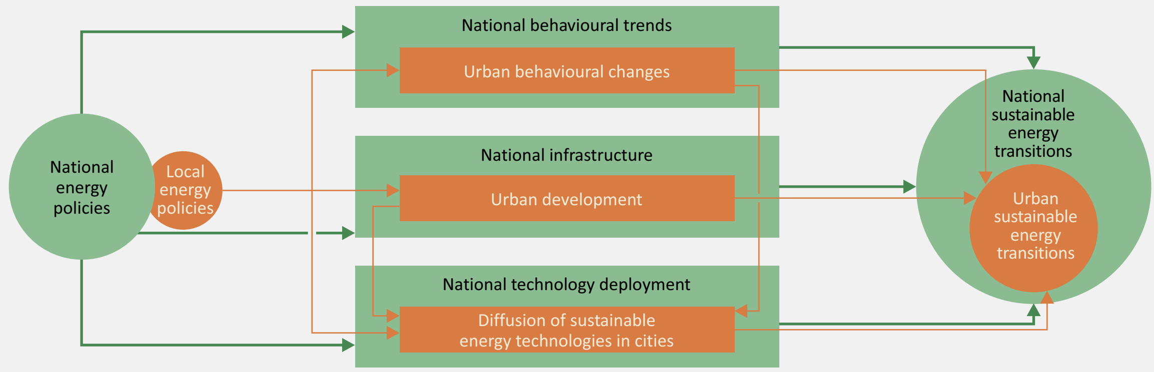
This chapter provides guidance to local and national policy makers to accelerate sustainable energy transitions at the urban scale. It first describes ways in which more effective integration of local and national policy making can foster energy transitions. It then provides an overview of the approaches available to local policy makers to support technology adoption and promote behavioural change leading to greater energy efficiency and renewable energy use in cities.

The chapter also analyses selected financing mechanisms and innovative business models that could mobilise the finance that is needed to achieve a sustainable energy transition.

Case studies show how policy makers can tap into the significant potential for cities to help achieve clean energy goals, while also highlighting various challenges such as costs and other limits to clean energy technology deployment.

Interaction between national and local levels can be best understood from a systems perspective (Figure 7.1). Sustainable energy transitions at the local level are embedded within the broader context of national transitions. They are shaped by national behavioural patterns, national infrastructure development and technology deployment spanning the different geographically situated energy systems of a country – urban, peri-urban and rural. At the same time, cities can be test beds or drivers of wider social (e.g. behavioural) and technological innovation, particularly as they are home to more than half of the world's population and generate more than 80% of global gross domestic product (GDP) (see Chapter 3).

Figure 7.1 **Interactions between national and local drivers of sustainable energy transitions**



Note: Figures and data that appear in this report can be downloaded from www.iea.org/etp2016.

Key point *Urban sustainable energy transitions both drive and are driven by national policy frameworks.*

Over the last 25 years, city governments have increasingly stepped up actions aimed at intensifying the sustainability of urban energy systems. In fact, several thousand municipalities across the globe have introduced plans to cut energy-related carbon emissions and air pollution, as well as to increase the resilience of urban energy systems to the impacts of climate change and other external shocks. This momentum needs to be accelerated, as cities are called to fulfil their role as strategic enablers of ambitious national and global sustainable energy scenarios (see Chapter 3).

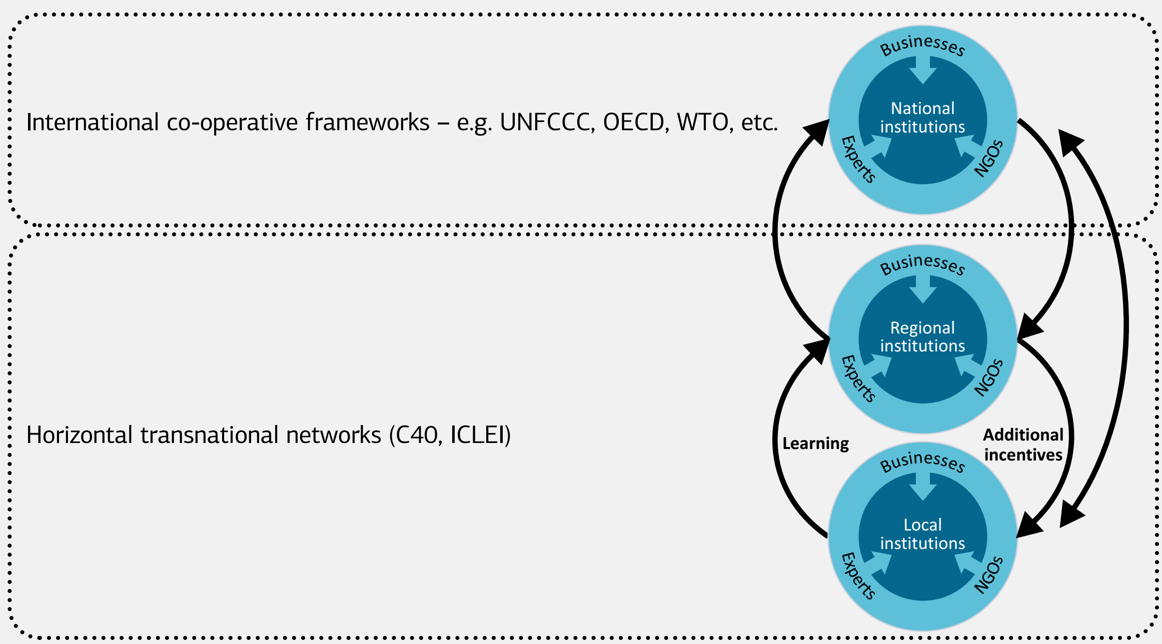
Without a strong policy push, the sustainable energy potential of cities is likely to remain largely untapped. It is essential to look at the wide range of planning and policy instruments available to cities to implement urban energy sustainability. The key to implementing effective sustainable energy policy is to apply a systems-based approach that can replace the conventional policy process of single-sector measures. To this end, national programmes and policy frameworks play a crucial role in enabling sustainable energy transitions at the local level.

Multilevel governance of energy

Energy policies are implemented within multilevel governance systems, which include the international level (e.g. multilateral agreements) and national and sub-national levels. These complex systems of governance call for a clear understanding of the interactions of all parties and what "entry points" can be used to improve governance capacity and energy policies to accelerate sustainable energy transitions at the local level.

The extent to which national policy makers can support local sustainable energy policies depends on the system of government – unitary or federal – and the number of governance levels, or administrative divisions above the municipality, whose decisions can affect local policy making. In federal countries such as Australia, Brazil, Canada, India, Mexico and the United States, sub-national governments have a very active role, and the division of power between the national and sub-national governments can affect the overall effectiveness of national energy policy.

Figure 7.2 The complex system of multilevel energy governance



Notes: UNFCCC = United Nations Framework Convention on Climate Change; OECD = Organisation for Economic Co-operation and Development; WTO = World Trade Organization; C40 = C40 Cities Climate Leadership Group; ICLEI = International Council for Local Environmental Initiatives.
Source: OECD (2010), *Cities and Climate Change*, http://dx.doi.org/10.1787/9789264091375-en.

Key point *Multilevel energy governance systems are characterised by a complex interplay of numerous actors.*

The effectiveness of multilevel governance depends on the degree of successful vertical integration (Broekoff et al., 2015) – the alignment of targets, policies and implementation under a coherent framework, across all levels of government

(national, regional, and local or municipal). Jurisdiction and authority should be distributed where the provision of services has the greatest benefit and cost (Oates, 1999). This means that while national governments are accountable for reducing GHG emissions, the powers to implement solutions that reduce GHG emissions should be allocated to sub-national governments where their direct benefits and costs apply.
As vertical governance frameworks are implemented to allocate powers to the most effective level of government, cities should emerge with three primary roles to achieve the urban sustainable energy potential:

- **Policy designers and leaders**: where a city identifies low-carbon solutions and leads with the design, implementation and enforcement responsibilities.
- **Key implementers**: where a city carries out action to achieve policies set by other levels of government.
- **Strategic partners**: where a city complements existing policies and targets and increases the marginal benefits and returns of other government policy (Broekhoff, Erickson and Lee, 2015).

Vertical integration also needs to be accompanied by horizontal integration. For example, many infrastructure policies carried out in cities need to be aligned with those of the surrounding cities. It is crucial that sub-national administrations, such as counties or provinces, have the power to successfully integrate city planning into broader regional planning frameworks of land use and transport.

The broader governance landscape also includes stakeholders such as experts (e.g. from academia, think tanks), non-governmental organisations (NGOs), communities and businesses. The complexity of these interactions needs to be clearly understood to ensure that energy policies are effective (Figure 7.2).

How national policy frameworks can promote sustainable urban energy options

National and regional policies frame the systems and rules in which cities act to achieve the urban sustainable energy system. National and regional governments have broad authority over the basic incentives for investment and behavioural decisions. Price supressing subsidies or low-tax regimes for fossil fuels limit the business cases for clean energy investment. Conversely, national frameworks that, for example, price carbon, set targets for energy efficiency and provide financial incentives for renewable energy production, can significantly leverage low-carbon solutions at the city level. These policies are “scene-setting” and have an influential role on the size and scale of ambition.

Cities need support from national governments because they often lack the financial and human resources, as well as the legislative powers, necessary to enact effective energy policies. But national policy frameworks, and dialogue between the national and urban levels, are often inadequate, leaving the sustainable energy potential of many urban areas largely untapped. This section proposes ways to connect national and local energy governance levels more efficiently.

National support for local governments and vertical integration between the two levels can take several forms, including (but not limited to):

- capacity-building initiatives that provide information and training for local energy planners

- national policy frameworks that provide local governments with legislative and fiscal powers to increase the effectiveness of local energy policies
- direct funding of local sustainable energy projects (Kern and Alber, 2008).

To meet municipal authorities' need to build their capacity, national governments can implement a wide range of programmes to support their cities, financially and technically, through training programmes. Capacity-building activities by national governments that have proved effective include sharing best-practice examples, publishing guidelines or manuals for local sustainable energy policy, implementing training programmes for local energy planners, and developing planning tools for local authorities.

National governments need to ensure they understand local decision-making processes in the energy, climate and environmental domains, and, most importantly, how those decisions are being implemented. National governments should also develop programmes that facilitate the use of standardised city-level data and analysis, such as Cities Leading through Energy Analysis and Planning (Cities-LEAP), a project initiated by the US Department of Energy (Aznar et al., 2015). Overall, national governments have a key role in promoting a standardisation of metrics on the impact of local energy policies.

National governments can also use benchmarking as an important element of enabling policies. To be successful, benchmarks need to be realistic. Governments can create such benchmarks for municipalities by drawing on examples of successful policies or projects carried out in other cities. Examples of possible benchmark metrics include per capita carbon dioxide (CO_2) intensity, per capita energy intensity in final uses, and final energy demand in buildings and transport. Such benchmarks need to rely on accounting or analytical frameworks developed at the international level. These frameworks could apply a conceptual approach similar to the Global Protocol for Community-Scale GHG Emissions (WRI, C40 and ICLEI, 2014). National governments could also launch sustainability awards to encourage friendly competition among cities.

Voluntary agreements between national and city governments can also be effective. For instance, certification programmes can be used by national governments to award certificates or labels to cities based on their performance on different metrics.

National governments can also help cities by easing legal constraints on the introduction of ambitious sustainable energy measures such as more stringent efficiency standards in buildings or tougher air pollution limits. The extension of municipal legislative powers needs to take into account the broader policy context. At the same time, the setting of more stringent local standards can provide useful information for national policy makers when deciding on national standards.

Another enabling role that national governments can perform is to support the activities of international city networks – such as C40, the Covenant of Mayors and ICLEI[1] – and cities' activities within these frameworks. The European Commission's strategic support for the Covenant of Mayors is an example that could be replicated by federal states or unions of sovereign countries (Box 7.1).

1 More information on C40, the Covenant of Mayors and ICLEI can be found at: www.c40.org; www.covenantofmayors.eu; and www.iclei.org.

Box 7.1 **Vertical integration between the European Commission and the Covenant of Mayors**

The Covenant of Mayors is an initiative launched by the European Commission in January 2008 to support efforts by cities or metropolitan areas to design, implement and monitor sustainable energy action. Bringing together more than 6 500 municipalities with a combined population of more than 200 million, the Covenant of Mayors is based on voluntary agreements by local authorities to increase the use of local renewable energy sources and reduce energy consumption so as to meet or exceed the European Union's target of a 20% reduction in CO_2 emissions by 2020.

The Commission provides technical assistance for the preparation of action plans and operates an office for co-ordination and networking among cities. The Commission also funded the creation of a facility for mobilising European Investment Bank (EIB) credits as part of a coherent multilevel governance structure involving the Committee of the Regions and the European Parliament. The EIB, a large multilateral lender owned by the EU member states, works with cities to help channel finance through local aggregators to smaller-scale sustainable energy projects, such as building retrofits and transport fleet upgrades (Covenant of Mayors, 2016).

National funding programmes can be established to support the implementation of sustainable urban energy plans. For instance, the French *Bilan Carbone* helps municipal areas to develop emission inventories. Funding programmes can support investments in sustainable energy infrastructure (e.g. refurbishment of public buildings, realisation of bus rapid transit systems) or other activities related to the implementation of local sustainable energy plans (SEPs), such as training local officials in the use of planning tools, research and data collection, education, and communication. Co-funding with city authorities is a prerequisite for effectiveness, and financial support from national governments can be given in the form of a grant or soft loan.

In addition, national governments can have a more proactive role in the regulation of local energy policies, such as minimum energy performance standards (MEPS) or specific local planning requirements. A MEPS linked to mandatory certification can be applied to existing municipal buildings, for example, requiring municipalities to invest in buildings' energy efficiency. National authorities can also require municipalities above a specific population size to develop local SEPs that establish minimum targets and require intermediate reporting.

The effectiveness of the regulatory approach taken by national governments depends on each country's multilevel energy governance structure. In countries where national policy authorities can have a strong, direct and rapid influence on municipalities, the regulatory approach can be efficient. In countries where sub-national governments have a strong role (e.g. in federal states), centralised regulation needs to work with the different jurisdictions of energy policy making in the most effective way possible.

Achieving sustainable urban energy systems: The role of local government

National emissions pledges and actions have tended to focus on measures that can be implemented across sectors of the economy and across geographic regions. National GHG emissions reduction pledges and policy frameworks often do not consider or incorporate the impact of urban climate actions. Cities have a unique and influential role over several key actions areas such as urban planning and public transport that are often outside the purview of national policy makers. This means that city climate actions are often additional to existing national GHG emissions reduction policies and frameworks.

The challenge for urban planning in the 21st century will be to include energy and sustainability objectives in wider land use and urban development policies. In many cities in developing countries, this would mean integrating zoning, land use development and transport network design in the early planning stages to accommodate urban growth that is energy efficient and that also meets multiple development objectives, such as job creation, access to services and public health. In more established cities in OECD member countries, the challenges are to implement low-carbon solutions into existing urban systems, in some places upsetting established local frameworks and in others adapting previous developments to achieve energy and environmental improvements.

Local governments have a key role in ensuring that sustainable energy objectives are a core focus of the various governance, planning, engineering, service delivery, development and commercial activities that compose the act of city-making. Within their boundaries, cities are composed of interwoven networks – for instance, residential buildings, commercial transport, information networks and energy distribution – that in many places are in constant change. This dynamism, and the constant push and pull between public regulators, private actors and the public, is acutely felt in the realm of energy demand and supply. The transition to sustainable energy needs to involve all actors that make up the urban energy nexus.

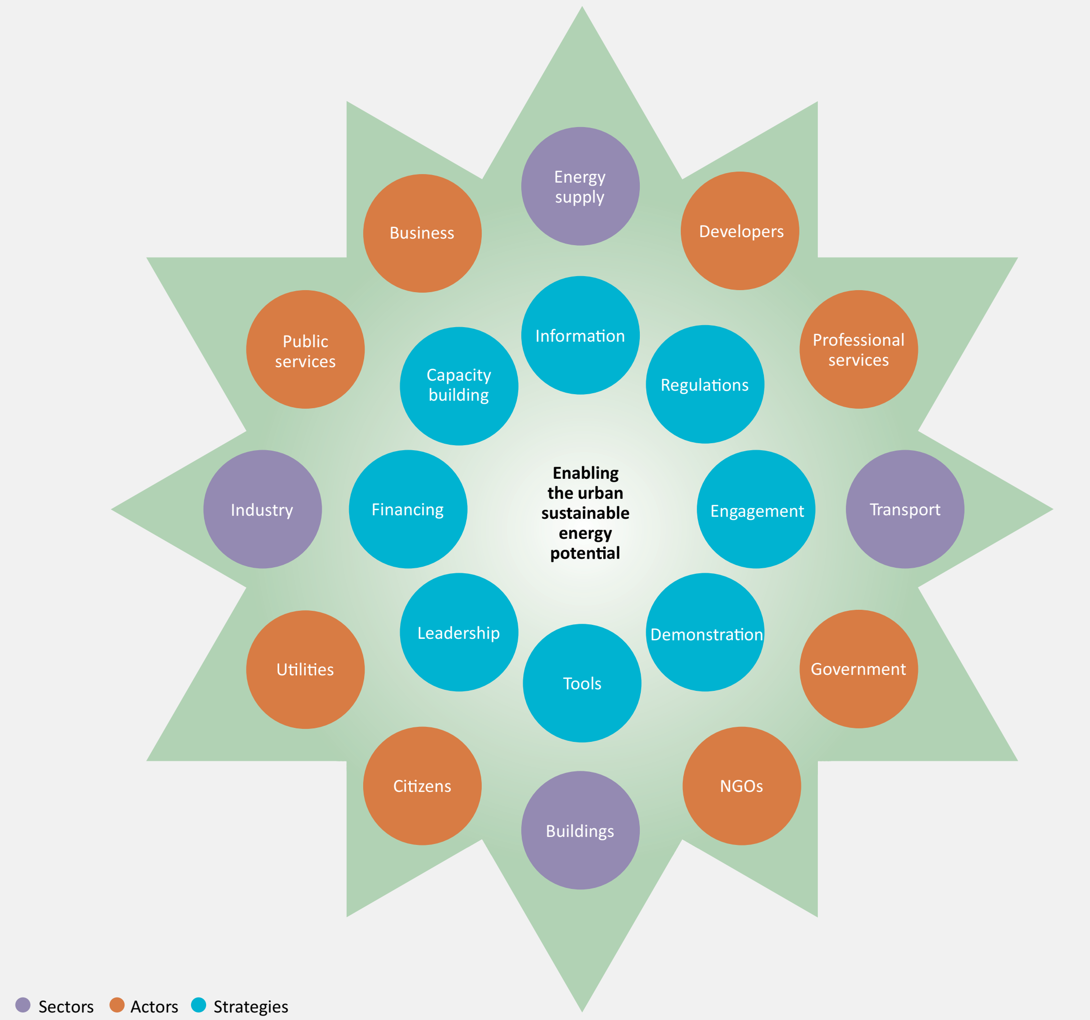
These actors include higher levels of government, developers, commercial enterprises, utilities (both local and regional), energy service companies (ESCOs), community organisations and NGOs, consultancies and contractors, and other institutions such as health and education authorities. Government policy can help these actors to pursue strategies to identify solutions for the major energy-consuming sectors (Figure 7.3). Strategies could include policies and regulations to deploy various technologies, financing and incentives for businesses to pursue energy efficiency and clean energy investment or engagement, and information campaigns to encourage citizens and institutions to shift to low-carbon activities and products.

The roles for these actors and the strategies they pursue depend on context and country. Cities in OECD member countries, which are largely already built, have more leverage points in governance mechanisms than many cities in non-OECD countries, which are still growing and defining their urban form. Cities in developing countries may have opportunities through unofficial channels (e.g. local community groups and stakeholder organisations) to address sustainable urban development, as official mechanisms and institutions may not be as well established. Identifying the right actors and strategic pathways to address the various energy-related sectors is therefore key to implementing potential energy solutions.

Policy tools for local governments depend on jurisdiction and authority

While the spectrum of powers at the disposal of municipalities and local governments is almost always narrower than that of regional or national governments, municipal policy choices can have large impacts on local energy and emissions footprints.

Figure 7.3 Sectors, actors and strategies to enable a transition to sustainable urban energy



Key point *There is a wide mix of actors and strategies needed to foster an enabling environment by which low-carbon actions can be pursued across sectors within the urban energy system.*

Urban planning, one of the basic functions of most municipal governments, has a crucial impact on energy intensity and energy consumption, through decisions on land use, urban form and transport infrastructure. For example, zoning requirements for higher-density developments affect the number of passenger trips by personal vehicle, public transport, and walking or cycling, and hence energy consumption and passenger transport efficiency. Higher-density developments often mean fewer square metres per person and lower heating and cooling loads in buildings. They also often offer more attractive business cases for district energy systems, which can take advantage of various low-carbon heating and cooling solutions.

All municipalities with basic planning powers can improve the energy efficiency of their urban energy system.

Most municipalities and local governments deliver services in which energy efficiency can be improved, including local energy and water utilities, public transport, social housing and sanitation. Municipalities are also typically large energy consumers themselves, owing to various public energy services, such as local street lighting and waste collection, and often large public building stocks, including schools, public or social housing, municipal offices, and other public fora.

In addition to these core functions, some municipalities and local governments enjoy broader powers to pursue specific energy policies. Cities may be able to develop their own, often more stringent standards and codes for buildings; offer financial incentives such as subsidies, financing and tax rebates for GHG-reducing actions and technologies; develop and manage low-carbon energy supply infrastructure; implement taxes on carbon-intensive activities such as transport; and plan and implement resilience strategies for energy supply and climate change impacts. Some large cities enjoy wide powers that overlap with national jurisdictions, enabling them to create carbon trading markets, for example (Box 7.2).

Box 7.2 **Carbon markets succeed in some large cities in East Asia**

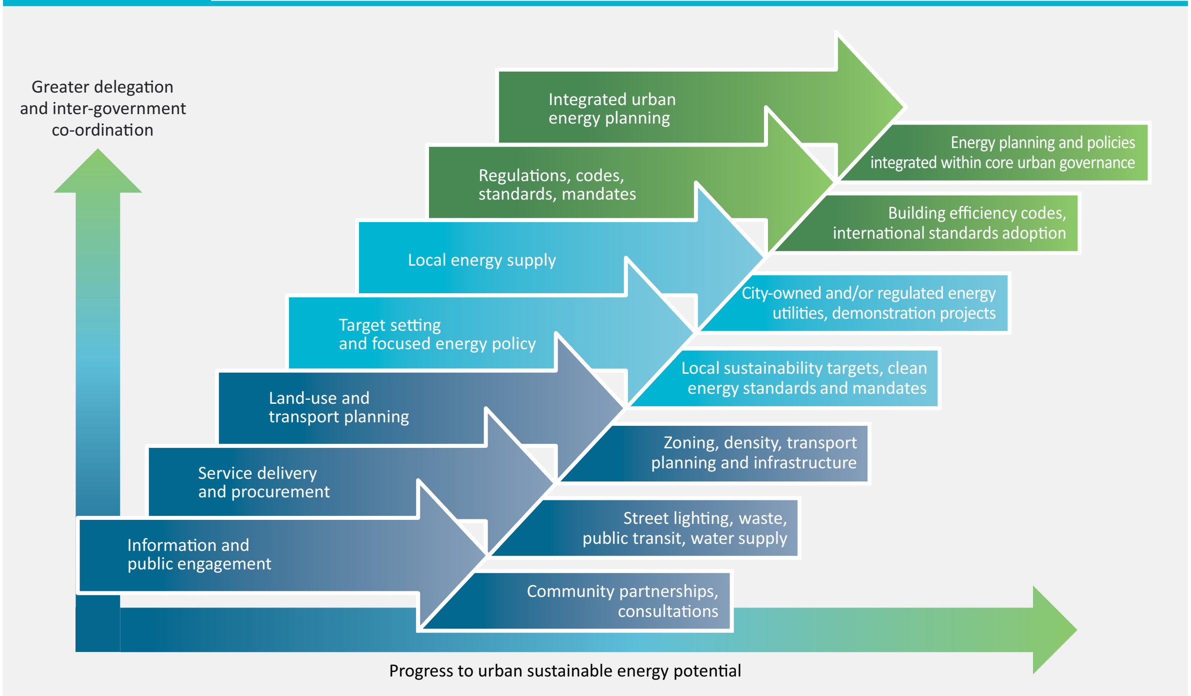
In 2010, Tokyo implemented the world's first city-scale cap-and-trade system, which sets emissions limits on buildings and industrial facilities with annual energy consumption of more than 1 500 kilolitres of crude oil equivalent. This covers over 1 300 of the largest emitters and 40% of commercial and industrial sector emissions in the Tokyo Prefecture. Buildings were required to reduce GHG emissions by 8% between 2010 and 2014 and 17% between 2015 and 2019. Industrial facilities had to achieve reductions of 6% between 2010 and 2014 and 15% between 2015 and 2019. Over 90% of regulated entities have exceeded their emissions reduction targets. On average, regulated entities have reduced their energy consumption by 15% from 2005 levels and more than 7% since the programme was implemented (IEA, 2015).

In China, the government set up emissions trading pilots in some major urban centres. By the end of June 2014, five city-level and two provincial-level cap-and-trade programmes had been implemented, covering 1 260 million tonnes of CO_2 and over 2 000 entities (CDC Climat and IETA, 2015). Taken together, the programmes amount to the world's second-largest emissions trading system. The programmes' design can be tailored to the local context while following national guidelines developed by the National Development and Reform Commission (Munnings et al., 2014). The Chinese government is learning from each programme as it prepares to launch its national emissions trading system. This experience emphasises the important function that cities can play as laboratories to help achieve national carbon reduction targets.

Policy options for sustainable cities

Cities can pursue a wide range of sustainable energy policies and strategies, depending on their powers and governance models (Figure 7.4). As cities move up the scale of action and achieve more of the sustainable energy potential, the number of possible strategies, policies and other actions widens along with the need for greater inter-governmental co-ordination and shared responsibility between key actors.

Figure 7.4 Taxonomy of policies to achieve urban energy potential



Key point *With increasing ambition to achieve the urban sustainable energy transition comes greater need for intergovernmental co-ordination and delegation.*

Information and public engagement campaigns

Cities have many opportunities to pursue public engagement campaigns that can improve awareness of sustainable energy solutions and influence citizen behaviour. Consultation and engagement processes are useful to help gauge public interest in sustainable energy policies and to tailor those policies to public priorities and needs. New zoning rules, by-laws and other city policy decisions can go through a formal consultation process to solicit feedback from local residents. In addition, many cities, especially in developed countries, have well-developed systems for resident feedback, questions and other requests for information.

Information campaigns can take place both at city level – such as sustainable development strategies, notifications for consultations and tax assessments – and at a more targeted level, through partnerships with community groups, local businesses and other important stakeholders to seek sustainable energy solutions (Box 7.3).

Box 7.3 Public engagement campaigns in Seoul and Helsinki

Since 2012, the Seoul Metropolitan Government (SMG) has implemented a diverse set of policies to save energy and improve efficiency under the One Less Nuclear Power Plant sustainable energy action plan. To nurture citizen engagement and energy activists, SMG delivers customised education to targeted groups through the Green Leaders training programme and the Youth Energy Guardian Angels programme, which operates in schools. This programme enabled schools involved to reduce energy consumption by 6.7% between 2011 and 2012, while also influencing household energy use. In addition, SMG has sought out partnerships with religious groups that have significant influence with congregation members.

SMG also promotes a wide range of mass participation activities aimed at more sustainable energy consumption. Campaigns include Happy Lights-Off, which encourages citizens to turn all their lights off for an hour once a month, and No Driving Day, which since 2003 has encouraged drivers to take a day off driving once a week; by 2013, around 820 000 cars had participated in the campaign. SMG runs the Eco-Mileage system, which provides participants with discounts on eco-friendly or energy-saving products, public transport and other public services if they reduce their use of electricity, water, natural gas and local heating; in 2014, over 1.9 million people were members of the system.

In Helsinki, city-supported public engagement initiatives can assist with improving awareness and addressing barriers for investment in low-carbon technologies. The Open Homes programme is an organised walk during which the participants visit a number of homes or public buildings that have recently made low-carbon energy investments. Neighbourhood residents and homeowners describe their investment and people can look around and ask questions. At the end of the walk a concluding discussion in a public place is held, so participants can talk about their own projects and interact.

Note: Information on Helsinki was submitted by Eva Heiskanen (University of Helsinki), Heli Nissilä (Aalto University) and Pasi Tainio (Finnish Environment Institute).

Procurement

Procurement of more efficient equipment, from lighting and buildings to city-owned vehicle fleets, is an effective and widely applicable strategy for local governments. Street lighting, for example, accounts for the largest electrical load and the largest single item of energy expenditure for many city administrations. Replacement of inefficient lamps with light-emitting diode (LED) lighting can significantly reduce direct electricity consumption and lifetime energy bills (Box 7.4), while providing additional benefits such as improved lighting quality, visibility and public safety. While energy efficient equipment offers long-term savings in operating costs, procurement often involves higher capital costs, so many cities may need to pursue phased approaches to procurement or alternative financing programmes.

As owners or operators of numerous public buildings and energy services, cities can also lead by example through energy savings programmes in municipal buildings. For example, public swimming pools can improve energy efficiency by reducing wasted water and maintaining optimal water and air temperatures. To achieve important energy savings, cities need to implement policies to track and manage energy consumption at public facilities, coupled with incentive programmes and targets for administrators that place energy efficiency first. Cities could realise the full potential of energy efficiency in publicly owned or operated buildings and services by working with ESCOs and other private ventures that have incentives to maximise cost-effective energy savings.

Box 7.4 **Staged street lighting procurement model in Auckland, New Zealand**

In 2014, Auckland Transport decided to replace 40 000 conventional 70 watt lamps with LED lighting. The procurement plan will last five years, which eases the annual capital outlay while maintaining significant lifetime cost reductions. Auckland Transport estimates that the new LED lamps will reduce energy costs by 50%. With a five-year phase-in, the annual capital costs are limited to 4.4 million New Zealand dollars (NZD) (compared with a one-year full replacement cost of NZD 22 million) and total lifetime savings of NZD 36 million (compared with one-year full replacement lifetime savings of NZD 40 million) (Auckland Transport, 2014).

Capacity building

Expanding the capacity of local governments to implement sustainable energy solutions is essential but often overlooked. Because of a narrow tax base and limited revenue-raising abilities, many medium-sized local governments and city administrations are supported by streamlined bureaucracies with minimal excess capacity beyond core functions. This means they often lack the capacity to identify, evaluate, implement and manage sustainable energy policies and projects.

Capacity building is a three-pronged process of: 1) improving the institutional and legal framework to support greater action; 2) shifting organisational structures to facilitate more effective management and decision-making processes; and 3) investing in the necessary human resources (Buss, 2010). Capacity-building efforts need strong leadership and explicit goals to realise their potential.

Policy options available to cities to improve sustainable energy capacity include investing in training programmes and dedicated energy administration staff; partnering with NGOs, businesses and consultants; and joining multi-city partnerships and processes that function as networks for exchange of expertise and information, such as C40, ICLEI or the Covenant of Mayors.

Water and waste service delivery

Many cities are responsible for managing energy- and/or carbon-intensive services such as water treatment and solid waste. Municipal solid waste (MSW) is a potential source of energy. In addition, organic waste – often the largest component of MSW – anaerobically breaks down into methane if sent to landfill, making landfills a potential source of energy or, if gases are not trapped and utilised or flared, of GHG emissions (Li et al., 2015).

Recycling and sorting waste streams can prevent large shares of organic matter from being sent to landfills and becoming potential sources of GHG emissions. Once diverted, organic waste streams can be used in local energy projects, such as bioenergy gasification plants, or they can be composted, with emissions benefits in both cases. Cities can also incinerate both organic and non-organic waste streams, avoiding methane emissions and providing heat and electricity.

Cities in most developed countries typically have large powers over the handling of their waste streams and are responsible for the costs of waste management programmes. The rapid increase in waste management costs around the world is an important incentive for recycling and diverting waste to its least costly and least carbon-intensive uses, and responsibly using waste as an energy source (World Bank, 2012). Policies available to cities include direct procurement and fees and charges to consumers and industry; communication campaigns promoting avoidance, reuse and recycling; and preferential treatment of waste energy where appropriate.

In much of Africa, India, and some parts of Latin America and South-East Asia, waste collection suffers from a lack of clear jurisdictional responsibility and service delivery models.

As a result, waste is often inadequately handled and is a major public health issue. Changing governance regimes, improving accountability, and running more effective sanitation services would improve public health and become a source of domestic energy supply in many developing world cities. Municipal policy and procurement can also help improve the energy efficiency of water supply and waste-water treatment, which are important sources of municipal energy consumption and GHG emissions.[2]

Water supply and waste water account, on average, for 35% of municipal energy consumption in the United States (EPA, 2013). In extreme cases, as in some desert countries with minimal renewable water resources, energy consumption for water pumping and desalination is a significant share of national energy consumption (IEA, 2015). Policies that can improve the energy efficiency of water provision include pricing mechanisms to reduce waste and overuse, and expanded monitoring and management of flows and losses to improve system efficiency.

Land-use and transport planning

The land-use and transport planning processes offer many opportunities to advance sustainable energy in cities. Land-use planning principles and priorities dictate the design parameters for developing new or existing urban land, including residential, commercial and industrial zones. The planning criteria for these zones are then defined further based on factors such as density and other physical design aspects of buildings, types of buildings and the businesses in a zone. Transport planning determines the infrastructure necessary to service developments. Land-use planning and transport planning are intrinsically linked: the form and pattern of development influence the transport infrastructure, and vice versa.

Box 7.5 Creating the spine of a city through long-term urban planning in Arlington, Virginia

The history of transport planning in Arlington, Virginia, has been typified by the city using all means to retain control over local urban planning. This was a confrontational approach because of city's location between Washington, DC, and suburbs that grew rapidly from the 1950s to 1990s in Fairfax, Loudon and Prince William counties in Virginia. Arlington's decisions have had a strong impact on the commutes for the growing population travelling daily from the suburbs into Washington, DC.

Arlington used a combination of mass transit planning (Metro rail) and restricted vehicle highway lanes to move people from personal vehicles to mass transit. Arlington insisted that the Metro be located in commercial corridors, rather than in the middle of a highway that was built through low-density residential neighbourhoods. These corridors at the time included low-density commercial development with large parking lots, and were prime targets for high-density redevelopment. At the same time, Arlington encouraged high-density neighbourhoods at major transit centres, which has enabled significant population and economic growth with building development.

In the Rosslyn-to-Ballston corridor, over 2.8 million square metres (m^2) of building development has occurred on 5 square kilometres of urban land, one-seventh of the space that would be required in a typical suburban development. Vehicle traffic decreased by 1% on the seven largest arterial roads from 1996 to 2006 while jobs and development increased significantly in the Rosslyn-to-Ballston corridor. At the same time, transit ridership increased, with the average daily entries and exits in four Rosslyn-to-Ballston Metro stations increasing from 31 664 in 1991 to 82 954 in 2008. This ridership increase was enabled by land-use planning that has resulted in 73% of Arlington riders accessing the Arlington orange line Metro stations by walking (Brosnan, 2010).

The combination of transit planning, highway restrictions and land-use planning has resulted in major spines of the city being developed along Metro subway lines. This planning has also created walkable city neighbourhoods while retaining the character of the older single-family home communities within walking distance.

As outlined in chapters 3, 4 and 5, urban density and transport networks have important impacts on the energy-consuming behaviour of people and businesses. Different urban forms and transport networks can promote more or less energy consumption with similar levels of services provided. Dense urban forms can improve the economic case for district energy systems, which can improve efficiency and enable the transition to a low-carbon residential energy supply. Higher density also can improve the economic case for public transport. Land-use planning can also have a more direct impact by offering financial incentives to developers to build more energy-efficient and sustainable communities.

Land-use and transport planning is a fundamental component of the urban sustainable energy transition. All cities, whether rapidly expanding or redeveloping, can promote housing, transport and commercial patterns that are less energy- and carbon-intensive (Box 7.5).

Target setting

By tracking energy use and GHG emissions, cities can set targets to reduce both. Target setting by local governments can be more effective than national targets because it can give local decision makers a greater sense of accountability for their policy decisions that will affect energy consumption and GHG emissions. Nationally, GHG emissions are affected by macroeconomic cycles and other factors outside the direct influence of most national political processes whereas local institutions can have a much greater impact within a specific local jurisdiction.

Box 7.6

Vancouver's Greenest City Action Plan motivates organisational change

In 2011, Vancouver implemented its Greenest City Action Plan with the goal of becoming the greenest city in the world by 2020. To achieve this, the plan set targets along three themes – zero carbon, zero waste and healthy ecosystems – and two overarching goals to 1) transition to a green economy and 2) reduce the city's environmental footprint. Each target is specific, measurable and accountable. Targets focused on energy are:

- reduce community-based GHG emissions by 33% from 2007 levels by 2020
- require that all buildings constructed from 2020 onward be carbon neutral in operations
- reduce energy use and GHG emissions in existing buildings by 20% from 2007 levels
- ensure the majority of trips are by foot, bicycle and public transit
- reduce the average distance driven per resident by 20% from 2007 levels (City of Vancouver, 2012).

The city's operations are organised around achieving the targets, with two four-year action plans from 2011 to 2014 and 2015 to 2020. The first action plan was a success, with significant progress towards the targets. The transport targets have already been achieved, and the city is on track to achieve the remaining energy targets, although more ambitious efforts will need to be implemented, such as expanding the city's low-carbon district energy system.

The interim success of the plan has led the city to build on it by creating further targets, including becoming 100% renewable-powered by 2050 (City of Vancouver, 2012).

Cities can also have greater influence over urban energy consumption and GHG emissions than national authorities, through policies on buildings and transport. Cities' building energy codes and zoning affect buildings' energy consumption. Municipal investments in public transport and other efforts to discourage personal vehicle use also affect energy use and emissions. As a result, target setting at the local level can potentially make for "fewer places to hide" for local leaders, which increases accountability and commitment to achieving targets.

Setting targets also provides incentives to track energy consumption and GHG emissions more precisely, so that progress can be evaluated. Building the necessary monitoring infrastructure and capacity is in itself a step towards realising the sustainable energy potential in cities. Data accumulation and analysis provide feedback on performance and can reveal more opportunities for action and improvement. The achievement of targets can build institutional and organisational momentum that may stretch beyond the target period and create lasting cultural changes to foster greater focus on sustainability. Competition to achieve targets can also lead to a "race to the top" within cities' various administrations as well as between cities.

Local energy supply

Local provision of electricity and heat in urban areas provides opportunities to improve efficiency gains and switch to sustainable fuels. Municipally owned energy utilities usually purchase electricity from generators, and they can own and operate some generating capacity themselves. For instance, the United States, Germany and other countries have used this model for over 100 years (Box 7.7).

Interest is growing in decentralising energy supply and increasing local ownership, especially of renewable energy production (see the following subsection on innovative models), a potentially significant development for the future of urban sustainable energy. Local energy supply options can take the form of district energy systems, local electricity distribution and generation utilities, and ESCOs. Cities can be whole or part owners of these.

In cities in developing countries, local clean energy supply infrastructure can help improve energy access and economic development while reducing pollution. Decentralised utilities can be more responsive to local needs by partnering with communities, businesses and NGOs to build smaller-scale power infrastructure such as micro-grids (World Bank, 2014).

There are numerous models for local energy supply, depending on: the type of energy supply and services to be provided; the national or regional policy framework for local authorities and their statutory powers; the existing energy supply business model and infrastructure; and the level of ambition that cities and their citizens want to pursue. Key policies for local authorities to implement are to identify successful financing and business models (see following sections); partner with power developers and community organisations; co-ordinate with other local governments and higher levels of government; and seek power supply agreements with large energy consumers or purchase agreements with local energy and waste energy producers. (Community Power Agency, 2014).

Box 7.7 **Germany's locally owned energy supply is a key cog in the sustainable energy transition**

In Germany, locally owned energy supply has been growing, through either local community associations or local utilities, as has their role in the German clean energy transition, the Energiewende. By 2012, 860 local utilities (*stadtwerke*) owned and operated electricity distribution systems and over 450 local energy co-operatives had been formed to own and run mostly renewable electricity generation capacity and distribution systems. The *stadtwerke* have grown in importance since the electricity system liberalisation of the late 1990s. They invested EUR 2.6 billion in electricity infrastructure in 2012 and account for 46% of retail electricity sales. Local energy co-operatives and citizens owned 47% of the renewable electricity capacity in 2012, taking advantage of feed-in tariffs (Schlandt, 2015).

As wind and solar power's share of electrical capacity grows, the energy system is becoming more decentralised because of the nature of these variable renewable energy sources. This change underlines the importance of local distribution utilities in managing the integration of renewables and, crucially, building new transmission and distribution capacity. Citizens have higher trust in local utilities to build new infrastructure and expand the grid in line with the needs of a renewable electricity system (Buchan, 2012).

Innovative technologies improve energy efficiency

"Smart cities" is a broad term to describe the many technological advancements that enable administrators to collect, monitor and analyse data on city systems and residents. These technologies allow cities to take advantage of and integrate the increased flow of energy, materials and people to improve system-wide energy efficiency, in part by influencing residents' behaviour. Collection of more precise information on the geographical, temporal and social dimensions of energy consumption creates opportunities for markets to develop and for new policies and programmes to be identified.

The potential of smart cities can be exemplified by the urban transport system. Cities have increasingly been investing in intelligent transport systems (ITS) to better manage traffic flow, provide more and better behavioural cues to drivers, and plan for more efficient transport network upgrades and additions. ITS use advanced monitors and sensors to evaluate traffic data, manage traffic signals, adjust speed limits, divert drivers to alternate routes, adjust road pricing signals, deploy more public transport capacity and aggregate data on road usage to plan system improvements. As local energy consumption grows and the use of electric vehicles increases, ITS can be linked with local energy supply information and management systems to predict spatial deployment and timing of electrical load and storage. As ITS technologies develop sensors to track walking and cycling, they will allow monitoring of the full transport system within a city, creating new possibilities to evaluate and alter transport policies (Box 7.8).

Better data collection and monitoring do not necessarily improve system efficiency; however, data need to be analysed and the findings integrated with those in other systems. The ability to monitor with greater precision also raises concerns on the safe and appropriate uses of data. Cities need to develop focused principles, policies and plans to integrate technological innovation into their operations and management while respecting the rights and freedoms of citizens and other stakeholders.

Governance frameworks and policies to support advanced technologies need to be locally specific but should typically incorporate principles focusing on:

- supporting innovation through openness, partnerships and ease of access for stakeholders
- seeking and empowering partnerships through protocols on transparency and service agreements with partners and stakeholders
- integrating information systems and city service functions with policy and planning objectives for greater efficiency and sustainable energy production
- improving governance and managing information, in alignment with public priorities (Lee and Gong Hancock, 2012).

Box 7.8 ITS in San Francisco (United States) lowers traffic volumes

San Francisco's high-tech and innovative dynamic parking pricing programme, SFpark, harnesses digital communication, data collection and sensor technologies to adapt parking prices by time of day, day of the week and location.

The pilot programme was inspired by proposals to alter parking prices and allocate parking spaces according to fundamental market principles to match supply and demand effectively and efficiently. The underlying idea is that prices can be adjusted during the day (every hour or every three hours, for instance) and in different areas to ensure that 80% to 85% of the parking spaces on each block are occupied at any given moment on average.

SFpark was implemented across eight neighbourhoods in San Francisco and affected both on-street and off-street parking. Drivers can use smartphone apps that display parking availability and prices in real time, and parking meters have been upgraded to accept coins, credit cards and city-wide public transit payment (SFMTA) cards.

The programme was conceived not only to allocate parking more efficiently, but also to reduce the total volume of driving in the city. A simulation estimated that the programme reduced "cruising for parking" by more than 50%, despite the city's booming economy and other trends that may work against the measure (Millard-Ball et al., 2014). Lessons from the programme offer great promise to other cities, including those where sophisticated equipment is not as readily available (Millard-Ball et al., 2014).

Regulations, codes, standards and mandates

Outside planning and zoning, most cities lack the regulatory powers to enact codes and standards that promote more sustainable products and practices. But this is changing as national governments recognise that cities need greater flexibility to deal with the challenges that come with increasing urbanisation and energy consumption. Many cities are being empowered to build on national policies, regulations and codes, particularly regarding energy efficiency for buildings and pollution controls for vehicles. Paris, France, for example, has an ordinance that requires new urban developments to exceed national building energy codes by 20%.

Extending regulatory powers to cities can also have benefits for higher levels of government. Cities can test policies for regional and national regulators to evaluate, and city-led regulatory efforts can build bottom-up momentum in other cities. Cities can lower the stakes of national regulatory efforts as capacity is built and lessons learned, essentially acting as policy laboratories (Box 7.9).

Box 7.9 **Los Angeles leads the way for ambitious green building standards in California**

In 2002 Los Angeles (United States) passed a Green Building Ordinance that required new municipally owned buildings with an area of more than 7 500 square feet (697 m^2) to earn Leadership in Energy and Environmental Design (LEED) silver certification. In 2008, Los Angeles updated the ordinance, requiring that developers submit LEED certification for new private buildings over a minimum size threshold (thresholds differ depending on the building type but are typically over 50 000 square feet). At the time this was the most stringent municipal green building policy of any large US city (Brown, n.d.).

Experience from the Green Building Ordinance fed into the development of California's 2010 building code, CALGreen, which was the first state-wide mandatory green building code in the United States and replaced the LEED certification with its own certification system. CALGreen is a comprehensive standard focusing on improving total resource efficiency in new buildings, including water use, waste diversion and energy efficiency. In 2011, Los Angeles passed the Green Building Code, based on CALGreen, with locally tailored amendments. New buildings are required to have infrastructure to support electric vehicles, and additions to existing buildings valued over USD 200 000 must adhere to the CALGreen standard (Younan, 2013).

The interplay between Los Angeles and other municipalities in California with state policy makers to promote green building regulations has resulted in flexible but mandatory new codes. Now many cities are building on the state codes, and the state-wide standard may undergo revisions and improvements based on city-level experiences.

In developing and emerging countries, powers to local authorities can be more decentralised with the creation of new cities and settlements to support special economic zones and the significant growth pressures they can manifest.

Even if most cities do not have strong regulatory powers, they still have jurisdiction to make by-laws that can reduce energy consumption and GHG emissions. Cities can mandate performance standards, targets and other low-carbon and energy efficiency attributes through their procurement and service delivery functions. Some by-laws aim to curb urban personal transport use and promote more efficient public transport In Bogotá (Colombia) cars with even-numbered license plates may be driven only on even-numbered days of the month, and those with odd-numbered license plates only on odd-numbered days.

Cities can also adopt standards that will help decision making, policy and service provision to achieve environmental objectives. One example is the International Standards Organization (ISO) 37120 designation for sustainable development of communities. ISO 37120 provides a framework for cities to better measure the performance of city services and quality of life. Any city or local government may adopt the standard, which helps cities to systematise the collection of data for management and evaluation of city policies and progress to increase liveability. To participate in the standard, cities must report on at least 46 core indicators and can track up to 100 indicators designed to measure social, economic and environmental performance.

Towards integrated community energy planning

To enable cities to maximise their sustainable energy potential, the policies and strategies outlined in this section need to be integrated into local governance. Energy efficiency and sustainable energy objectives need to be put at the core of urban planning and the routine operations and management of city services. Cities must begin to recognise themselves not only as the layers of citizens, businesses, buildings, vehicles and services but also as energy systems that animate a city's liveability and commerce.

Box 7.10 From eco-industrial park to urban district: The green shoots of integrated energy planning in China

In 1994, China established an eco-industrial park in Suzhou, Jiangsu province, in collaboration with Singapore. This industrial cluster aims to help industrial companies to recycle resource flows to reduce their environmental impact. The park has now become an eco-district with 781 000 residents and contributes 15% of the city's GDP.

Energy-intensive industries and coal-fired boilers have been banned since 2007. Since 2010, energy audits have become mandatory for all companies with energy consumption of more than 3 000 tonnes of coal equivalent a year.

The district has also created an incentive fund for energy savings with an annual budget of CNY 15 million. Investment in energy efficient equipment can be subsidised by up to 20% of capital costs. Companies can also reduce energy audit fees by up to 50%. Each year, this funding can support approximately 60 projects involving 100 companies. Since 2012, additional funding has been allocated to the buildings sector, with the implementation of green building certificates, energy efficiency labels and retrofits of existing buildings. Voluntary approaches complement regulatory and economic instruments. By 2012, around 200 organisations, including companies, schools and residential neighbourhoods, had been granted the certificates recognising their awareness of energy conservation and environmental protection. Non-profit business associations, such as a low-carbon business association initiated by 36 energy companies in 2010, have helped to provide training and consulting services (Yu et al., 2015).

All the district's public utilities, including power generation, steam supply, natural gas, water and sewerage, are centralised and operated by Suzhou Industrial Park Public Utilities Company, which serves both business and residential areas. Waste water is recycled to treat industrial and domestic sewage. Sludge derived from this waste water is dried and used as a fuel to generate electricity, achieving energy saving of 12 000 tonnes of oil equivalent per year. The ash from sludge incineration is used to produce construction materials. Waste heat in the drying process is collected and reused in the co-generation plant,* which saves water and heating costs equivalent to CNY 1 million per year. The two gas-fired co-generation plants have an installed capacity of 360 megawatts and supply steam to 90% of the district. The waste heat from electricity generation is used to provide district cooling through an absorption chiller. Overall, the district's energy efficiency improved by 4.6% annually between 2005 and 2011, decoupling energy consumption from economic growth.

* Co-generation refers to the combined production of heat and power.

Many different tools, models and frameworks have been developed to assist the process of integrated urban energy planning. There is no "one size fits all" template for local governments to apply. Each city needs to adopt and integrate the most appropriate mix of the policies outlined in this section, in consultation with citizens, businesses, energy providers and technology firms and in co-ordination with other cities and higher levels of government.

Cities depend on developers, contractors, engineers, industry and other stakeholders to design and implement locally specific solutions. All of a city's energy systems, statutory powers, and management and governance processes need to be reoriented towards improving sustainability and reducing GHG emissions.

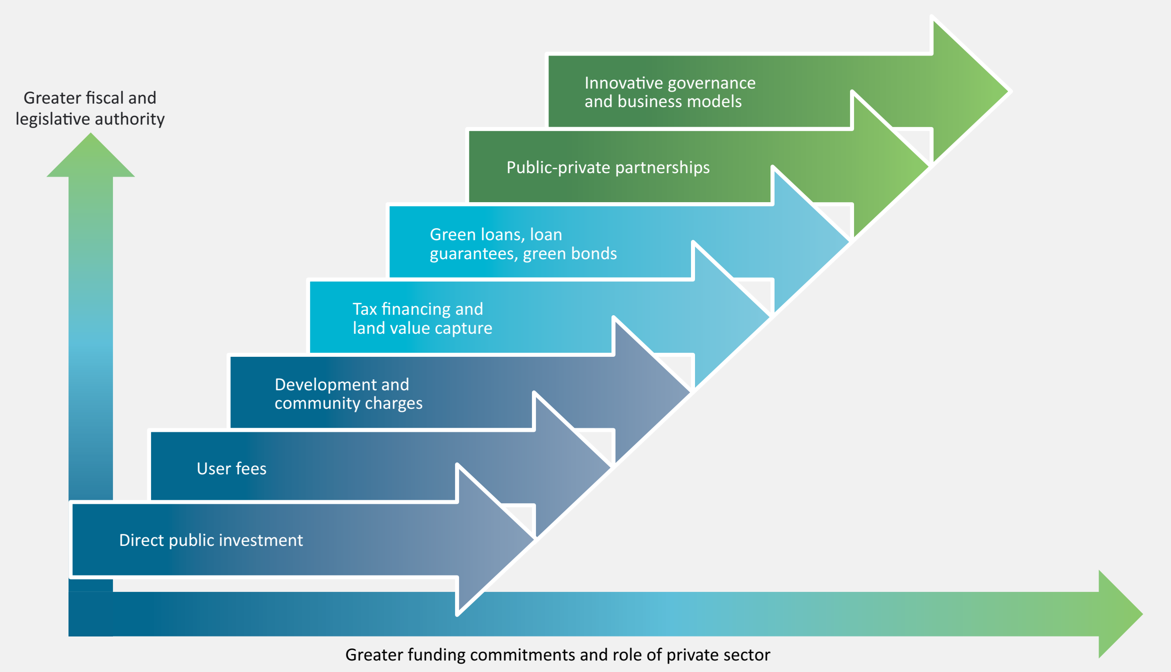
In developing countries with many rapidly growing cities, integrated urban energy planning may have even greater impact. As new buildings and services are needed to support growing populations, these principles can be readily applied at the outset of many city planning decisions (Box 7.10).

Financing urban sustainable energy

Making the transition to a sustainable energy system invariably involves more investment. However, most cities have narrow tax bases and limited powers to raise revenue, so much of this new investment must come from additional sources, and via new financing and business models (Merk et al., 2012). This section outlines finance mechanisms that can enable the transition to sustainable urban energy systems.

Government action alone is unlikely to be sufficient to finance the efforts required to achieve the urban energy potential. Because the amount of funding required will be beyond the means of most public sources, private financing and commercial business will need to be leveraged to provide the bulk of financing. Public policy that strengthens the market for low-carbon investments can serve as leverage to the private sector, which typically seeks out and undertakes innovative approaches to develop and finance projects. As the ambition to achieve more investment in sustainable energy grows, the greater the total financing required and the larger the role for leveraged private lending and business models (Figure 7.5)

Figure 7.5 **Mechanisms for municipal governments to finance urban sustainable energy**



Key point *The need for effective financial instruments to pace with growing ambition will require greater fiscal and legislative authority and leverage of the private sector*

Direct public investment and strategies for municipal low-carbon investments

Public financing will be a key component of the total new financing for urban sustainable energy, because publicly owned infrastructure and services will account for a significant portion of the investment needed for the transition. The higher the investment costs, the greater the need for co-ordination and cost-sharing among different levels of government. This includes allocating fiscal capacity to the levels of government that are able to cost effectively finance low-carbon investment (Box 7.11).

Box 7.11 Green Municipal Fund in Canada

Canada is a decentralised federal state where the ten provinces have jurisdiction over the governance and financing of municipal government. This has typically meant that the federal government, with the largest tax base and fiscal capacity, is distanced from the financial needs of municipalities. Recognising the funding gap facing most municipalities, the federal government created the Green Municipal Fund (GMF) in 2007 with an endowment of 550 million Canadian dollars (CAD), administered by the Federation of Canadian Municipalities (FCM), a non-profit group representing Canadian municipalities (Environment Canada, 2012).

All Canadian municipalities can apply for GMF project funding so long as the municipality has a sustainable community plan (for which the fund covers 50% of the cost). The fund offers grants covering 50% of the costs for early-stage feasibility studies along with grants and loans for capital projects. Loans and grants can cover up to 80% of a project cost up to CAD 10 million. Eligible projects include infrastructure initiatives in five categories (brownfield redevelopment, energy, transportation, waste and water) that benefit the environment. By 2015, the fund had committed to over CAD 700 million in funding, including 770 feasibility studies and plans and 119 capital projects (Federation of Canadian Municipalities, 2015).

The GMF is an example of co-ordination among different levels of government to expand the financial resources available to municipalities. This solution to the funding gap between the federal and municipal governments provides federal funding but devolves oversight and administration to the municipalities themselves. The FCM, as a body representing municipalities, was able to create the fund to better appeal to and serve municipal interests, while the endowment nature of the fund ensures that financing is responsibly provided.

Low-carbon infrastructure and services will likely be more costly (at least in the short term) than municipal governments' business-as-usual infrastructure and services, so transitioning to sustainable energy can strain the fiscal model for many municipalities. Direct public investments paid for through budgeted government accounting are a significant source of finance and investment. There are a number of strategies municipalities can pursue to incorporate low-carbon investments with higher capital costs. These include a broader and longer accounting scope, taking into consideration the longer-term benefits generated by low-carbon investments.

Multiple account evaluation and the multiple benefits of low-carbon investments

Valuing the multiple benefits of energy efficiency and low-carbon investments, which not only save energy but also improve air pollution, health and energy security, among other beneficial outcomes (IEA, 2014), can improve the business case for these investments. A cycling lane in and of itself may not have positive financial returns to a city in a standard accounting evaluation. But, if indirect energy, environment and health returns, from the shift in transport away from private vehicles are all taken into account, the benefits can outweigh the investment cost. Roadway infrastructure requires significantly more maintenance than cycling networks, and mode-shifting alone could pay for the cycling network over the medium term. Likewise, low-carbon district energy systems may have much lower criteria air emissions, which reduce health risks, and can have more reliable and secure energy sources with lower long-term operating costs and risk.

Natural capital valuation

Valuing natural capital expands the accounting scope of city planning and decisions in order to avoid degrading benefits that municipalities reap from natural systems. These systems could be wetlands that help filter water resources and provide flood protection or forests that provide air filtration, shade, soil stability and economic value, such as tourism and forestry jobs. Municipal development patterns and infrastructure could disrupt or strengthen different natural systems. Valuing these systems could place higher emphasis on minimising disruption with more compact and green development. If suitably incorporated into municipal planning and accounting, natural capital valuation could help improve the costs of development.

The city of Sanya, China, a tropical tourist destination on Hainan Island, recognised the impacts of rapid economic development on its natural capital endowments. If development were left unchecked it would harm the tourism industry and local employment. The city conducted a study estimating the value of the natural resources within the city's region and found that it had a natural capital endowment of USD 40 billion (Nixon, 2015). The city developed a balance sheet tracking the changes in its natural capital endowments. By valuing the natural assets in the city's region, development plans and city business can be conducted with a broader perspective of their impacts on these endowments, potentially strengthening the financial case for more sustainable development.

User fees

All cities charge user fees for services such as city-owned parking spaces. The rate and applicability of parking fees can strongly influence citizens' decisions in regard to personal transport. High parking fees are an effective tool to alleviate congested city centres by increasing the cost for vehicle commuters. User fees on waste volumes, water delivery and other city services could be adjusted to provide "greener" price signals to city residents.

Cities that are empowered with greater policy powers can pursue other meaningful user fee models, such as road tolls and congestion charges. Congestion charges, implemented in cities such as London and Stockholm, charge people who drive their vehicles into the city centre. This is an even stronger incentive for lower-carbon transport options, as all vehicle traffic is charged. Road tolls play a similar role to discourage vehicle use.

User fees for high-carbon activities not only discourage the behaviour but also generate revenue to be cycled into financing sustainable energy solutions. In the case of parking, fees designed to facilitate motorist convenience generate less than 1% of municipal revenues, whereas parking fees designed to maximise revenues could generate 5% to 10% of municipal revenues (Litman, 2015).

Development and community amenity charges

Municipalities collect revenues from property developers, known as development fees, which can be used to pay for parks, community centres, libraries and other public amenities. By increasing these fees – and adjusting charges for the amenities themselves – cities can help fund investments in sustainable energy infrastructure. Municipalities need to take care, however, not to render new housing developments uneconomical by imposing fees that are too high.

Cities can return value to developers who incur higher costs by constructing buildings that are more energy efficient or that are ready for connection to district energy systems. One way is density "bonuses", whereby density limits are eased for developers who achieve building energy performance above the normal local or national building energy code standard. This allows developers to build more units to increase revenues. Density bonuses can be used as an incentive to promote green building developments. For example, developers can qualify for higher density approvals (such as buildings allowed to exceed height thresholds with higher prices on more upper floors) in return for more developments with higher efficiency.

Land and property taxation

Cities often have control over the taxation of land and property, which they can use to encourage sustainable development. In general, taxes on land value tend to favour dense development, whereas property taxes can encourage unsustainable urban sprawl (OECD, 2015).

When cities invest in public goods and infrastructure that increase the value of local properties – for example, public transport lines to under-serviced neighbourhoods – they may attempt to recoup some of their money in the form of land-value capture. Cities that build public transport may make deals to receive a share of the value created for local property owners from new projects, whether through taxation at the point of sale or through adjustments to annual land or property taxes.

Tax financing has been used primarily to redevelop blighted urban regions. In this model, development subsidies and loans are provided to stimulate redevelopment of communities. When a zone is successfully redeveloped, the increased tax take from higher property values and economic activity is used to pay for the subsidies and loans. This model could work to stimulate the deployment of low-carbon infrastructure and renewal within a redevelopment plan.

Strengthening the investment market for sustainable energy development

Governments should aim to bolster commercial interest with the goal to create and strengthen a viable, well-functioning market for low-carbon projects and investment. Both national and local governments have roles to play, via policies and financing schemes, to make investments in low-carbon urban energy solutions more attractive and viable to the private sector.

The objectives for government engagement to support private low-carbon financing are threefold: 1) to strengthen the market with policies providing longer-term certainty and confidence for private investors; 2) to enable competitive returns on investments; and 3) to reduce risk (OECD, 2012). Critically, as municipal governments attempt to attract more private capital, they will more often need to be endowed with greater powers and ambition to enable low-carbon investment. National governments must work with local governments to transfer fiscal capacity and/or work to create a supportive policy environment where municipalities can take action. Strategies and financing mechanisms to support these objectives are described below.

Soft loans, loan guarantees and dedicated green energy funds

Governments can generally borrow at lower costs than private borrowers because of their lower credit risk. A city may use its balance sheet to guarantee loans and reduce the financing costs for private developers. Many cities already engage in this type of behaviour by socialising different forms of financial risk when building public-private capital projects such as sporting venues. Cities can enable private investment, in the case of leading demonstration projects, by providing loan guarantees when private lenders may be unwilling. This is possible where cities have the power to back loans and/or issue debt.

Government soft loans and loan guarantees can reduce the "soft costs" facing many private financiers such as lack of understanding or experience, which mean higher risk premiums. Government funds can offer favourable loan terms such as low rates, or take on a share of the loan default risk by covering any initial losses. As private lenders gain experience and confidence in these types of projects, the financing arrangement could transition to lower need for government risk-sharing.

Dedicated green energy funds could be a source of financing where eligible projects must meet minimum environmental criteria. Credit lines with low interest rates provided by municipal or national governments to facilitate green investment are one basic example of this approach.

Green bonds

Cities with the power to issue debt can issue green bonds with the purpose of investing in energy efficiency and clean energy. The difference between a regular municipal bond and a green municipal bond is the stated intention that the green bond financing is to be used only for projects that improve environmental outcomes.

The use of green bonds is growing. In 2014, the value of green bonds issued increased by USD 26 billion to USD 37 billion (Green City Bonds Coalition, 2015). In the United States, the first municipal green bond was issued in 2013 for USD 100 million. By 2014, USD 2.5 billion of municipal green bonds was issued. This growth represents both the strong demand for these products among bond investors and the appeal of this type of financing for investors in low-carbon technologies and infrastructure.

Municipal green bonds are not only the purview of cities in developed countries; emerging countries are also interested in and issuing green bonds. In 2014, the city of Johannesburg, South Africa, issued Africa's first municipal green bond for ZAR 1.5 billion (USD 139 million). The proceeds of the ten-year bond are to be used for renewable energy, waste-to-energy plants and hybrid-electric buses.

Public-private partnerships

Public-private partnerships (PPPs) are well suited to assist with deploying low-carbon infrastructure and carbon-reducing projects and services. The basic concept of PPPs is to identify, design and invest in projects that share risk and benefits more efficiently among public institutions, NGOs and/or private firms to reduce barriers for developing and deploying infrastructure and services. An effective PPP merges the risk-sharing benefits of public investment with the technical expertise and deployment efficiencies of private firms or NGOs.

Not only are PPPs already used for infrastructure development, but they are also beneficial to municipalities that lack the capacity to source and manage low-carbon technologies that are just beginning to be deployed commercially. The municipal government may have the financial resources to bear greater financing risk and can sign a long-term contract for terms of service too onerous for a private firm, but often lacks the expertise to build and manage a complex low-carbon energy system or energy efficiency upgrades. Specific PPP models are discussed below.

The PPP model works in both developing and developed countries. The International Finance Corporation leveraged USD 2.7 billion of private investment in PPPs in 2015 in developing countries for both national and municipal projects (IFC, 2015).

Energy performance contracting

Energy performance contracting (EPC) is a specific type of PPP in which a firm (often an ESCO) enters into an agreement with a municipality or public institution to make energy efficiency improvements. There are many types of EPC arrangements, but the general model is that the firm performs energy efficiency improvements and is paid back by the energy savings from the measures. For example, an ESCO enters into an agreement with a municipality where it pays for all of the energy efficient equipment, installs the measures and guarantees a performance level. In return, the ESCO is paid out of the financial savings from lower energy consumption of the measures over a specified period. After the period has expired, the city enjoys the financial savings from the decreased energy consumption. The specific terms of an EPC depend on the specific projects and its partners. But this model holds significant potential to scale up energy efficiency investment cost effectively in both OECD member countries and developing countries (Box 7.12).

Box 7.12 EPC pilots for efficient street lights in Europe and India

The Streetlight-EPC project funded by the Intelligent Energy Europe programme was launched in April 2014 with the objective of triggering the market uptake of EPCs through refurbishment projects for street lighting. This project is creating demand and supply for EPC projects and implementing a market development process that achieves critical mass – including 36 EPC street lighting projects over the project's three-year lifetime, many of which are already under way. In addition, regional EPC facilitation services have been set up in nine European regions.

In Bhubaneswar, India, the city – with assistance from the International Finance Corporation – entered into an agreement with an ESCO to replaced burned-out street lights with more efficient lamps, saving at least 30% in energy costs. The ESCO agreed to replace the bulbs and provide maintenance services, and was paid based on the shared savings of the project. The ESCO also received a fee from the money the city was saving by handing off maintenance duties. The city was responsible for monitoring and verifying the energy savings and the local electricity distribution. The agreement is expected to generate annual savings of USD 100 000 and leverage USD 4.8 million in private-sector investment (IFC, 2013).

Note: The Streetlight-EPC section of this box was submitted by Christiane Egger of OÖ Energiesparverband, www.esv-en.at.

Supporting clean energy financing with legislation

Higher levels of government with legislative powers over tax and credit payments can incentivise private investment in clean energy. For example, legislation can be enacted to prioritise the repayment of loans for clean energy and energy efficiency in the event of default, which would lower the credit risk and financing costs for these loans.

National and regional governments can also expand the tax base, the borrowing powers or the type of credit that can be issued by local governments, giving municipalities greater flexibility and agency to pursue clean energy programmes. Legislation to allow for municipally supported loans for clean energy to be paid back on property tax bills could lower the financing costs of loans and widen their appeal. Property tax payment rates are traditionally high in many cities, and the payment and collection infrastructure already exists for cities, lowering costs and administrative burden. Property taxes are typically at the head of the queue for repayment in the case of bankruptcy, further reducing the risk of default.

For example, legislation allowing for property liens on loans for clean energy and energy efficiency would improve the economic case for investments with payback periods longer than four to five years. This change would allow for loans on the property rather than the individual. With a loan that transfers to the new property owners, the financing is paid by the individual who is enjoying the benefits (typically in the form of energy savings) until the loan is repaid. This legislative change is one component of the property-assessed clean energy (PACE) financing model used in the United States (Box 7.13).

Box 7.13 PACE financing in the United States

The PACE programme is a state and local government initiative created in the United States in 2008 to facilitate the financing of energy efficiency and renewable energy projects in buildings. Building owners pay for improvements through specific assessments on their property tax bills or through utility bills (when the utility is municipally owned). The geographical scope of PACE programmes can range from single municipalities to counties. Commercial programmes have raised about USD 211 million for energy efficiency and renewable energy improvements in 522 buildings (PACENation, 2016).

The source of funds for PACE programmes can be local government general funds (e.g. county treasuries), municipal bonds (e.g. micro-bonds), private investment firms or bank loans. Banks (including investment banks) can also play a key role by purchasing bonds issued by municipalities. The most common financing structures adopted are warehoused finance, pooled bonds and the "owner-arranged" model, where building owners negotiate financing directly from capital providers (LBNL, CCI and Renewable Funding, 2011).

The first step of a typical PACE programme is the introduction of enabling legislation by states. Local governments then establish provisions for PACE implementation (e.g. ordinances creating assessment zones and authorising lien creation and project financing) and administrative and funding processes. Financing (e.g. through bond placements) then needs to be arranged by municipalities, consortiums or state agencies. Once the institutional set-up is in place and financing is secured, the actual implementation begins with contractors conducting energy audits on buildings. Building owners evaluate the different options available to reduce energy costs and, if need be, notify existing mortgage lenders of the assessment, requesting their consent to subordinate. Upon approval, a PACE "contract" is signed, local government financing is provided (adding the assessment to the tax roll and placing a lien on the property) and finally, the PACE-financed project is realised.

The advantages of commercial PACE financing include the absence of up-front costs, lower interest rates and higher debt terms than offered by commercial banks, no increase in corporate debt, potentially increased building value, and the possibility of transferring the assessment should the property be sold, so the obligation to repay the improvement costs is attached to the property rather than to the individual owner.

If efficient institutional arrangements are not in place, however, the structure of PACE programmes (with as many as six institutional-administrative steps before projects are realised) and the involvement of several levels of governance (municipalities, counties, states) could result in high transaction and administrative costs. Such costs would be burdensome for the local municipalities managing the different stages of the funding process and property tax assessment implementation. To prevent high transaction costs, effective vertical integration among the different governance levels is needed to ensure the maximum net benefits of a PACE programme.

Innovative governance and business models

In traditional, liberalised or regulated energy markets, the public utility in charge of distribution generates revenues by selling energy units to its final customers. Utility revenues are used to cover operating expenditures and network investments, and then profit is allocated to shareholders (including the public sector). This conventional business model may not be adequate, however, to accelerate the uptake of sustainable energy options such as demand-side management or building retrofits, or to give small-scale independent power producers access to customers. Alternatives to centralised approaches to energy delivery may be appropriate; these can also secure a wide range of other environmental, social and economic benefits for local communities (Hall and Roelich, 2015).

Box 7.14 Using policy to support business model innovation in urban energy systems

Though cities have found innovative ways to pursue change in energy systems, the pace of technological development means the opportunities for civic engagement in energy systems are still growing exponentially. New opportunities in demand management, aggregation and storage mean a wide range of new energy business models is being made possible (Hall and Roelich, 2015).

Research at the University of Leeds identifies nine new business model innovations in the UK electricity market that utilise these technological developments to better facilitate urban energy systems (Hall and Roelich, 2015). These include peer-to-peer software platforms that make a direct link between generation and consumption, and community-scale aggregation and balancing that optimise local generation and demand before drawing on the national market for top-up power.

Each new business model will deliver a different set of values to the energy system. Some may incentivise more distributed generation while others might focus on matching demand to off-peak prices.

At present, however, technological innovation is outpacing the commercial and regulatory innovations needed to fully exploit the potential of smart urban energy systems. The key message from this research is that fostering business model innovations in energy systems should be a key function of market regulation and national energy policy. In order to foster these new business models in urban energy systems, regulators and policy makers need to make space for experimentation and market testing. This may mean funding trials of business model and regulatory innovation as well as technology research and development.

Innovative business models and governance approaches have recently emerged that aim to meet final energy service needs while fostering energy efficiency improvements and local generation from renewable sources. Under the Energy Service Utility (ESU) model, the utility provides energy services (e.g. on-site renewable electricity supply, energy storage, thermal comfort) rather than supplying physical units of energy through the grid. An ESU could operate successfully in parallel with conventional investor-owned utilities, co-ordinating all energy flows and services through the network to ensure that supply meets demand in a new market environment.

Local authorities have already been proactive in supporting the uptake of sustainable energy in cities, either through conventional municipal utility or ESCO business models. For instance, municipal utilities can offer energy service programmes like demand-side management or, in principle, operate a de facto ESCO business model. Municipal utilities are best positioned to balance local demand with local supply from independent power producers. They can also be effective in managing advanced metering infrastructure and in accelerating the deployment of smart grids. By being actively involved in developing and deploying innovative business models, municipal authorities (and citizens) can be at the forefront of sustainable energy transitions.

Two innovative sustainable energy business models warrant more detailed analysis: the Sustainable Energy Utility (SEU) model and the Integrated Utility Services (IUS) model. In the basic SEU model, a new organisation is created to accelerate sustainable energy investments at the local level. With the IUS model, on the other hand, an existing municipal utility is restructured to drive energy sustainability transitions at the local level without jeopardising the utility's revenues.

The SEU model

The SEU operates as a "community utility" tasked with the management of financing programmes that support community-scale investments in energy efficiency and renewable energy technologies. The concept was first developed in two research papers (Byrne and Toly, 2006; Byrne et al., 2007) (see Figure 7.6). The SEU, which can be organized by cities or larger administrative units, also works as a clearing house for the implementation of energy sustainability programmes; these programmes are then used to deliver energy services to the communities served (Byrne and Taminiau, 2015).

The SEU model, first deployed in Delaware in the United States in 2011 and also in effect in Washington, DC[3], potentially provides an effective model of sustainable energy governance for municipalities. The model can be adapted to local circumstances (e.g. it can rely on existing agencies while applying the same sustainable energy financing mechanism) and can be based on different financing options (e.g. bond financing programmes, surcharges or revenues from Regional Greenhouse Gas Initiative [RGGI] auctions); the following describes the model as it was applied in Delaware.

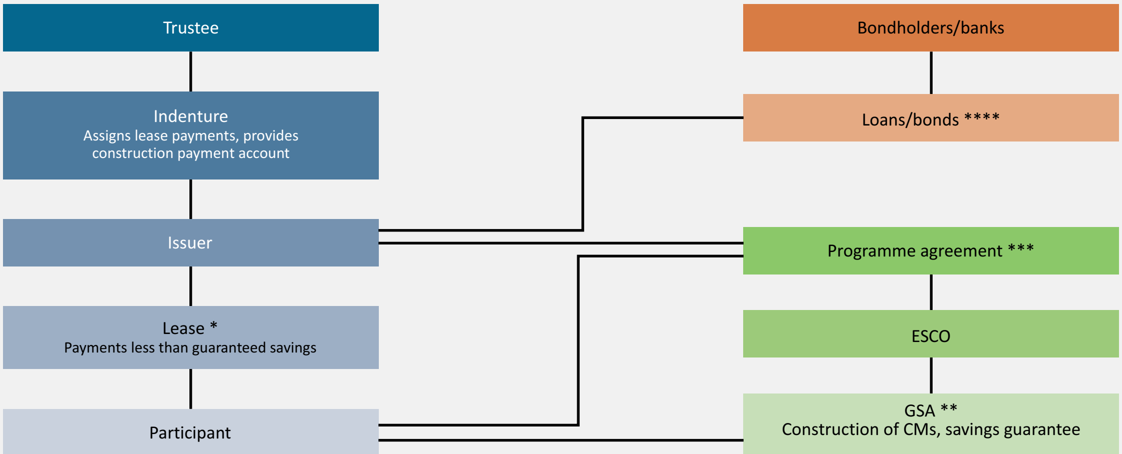
The first cornerstone of the SEU model is the emission of appropriation-backed bonds, which are backed by contract performance guarantees.

The financial resources collected from investors are then used by the SEU to provide financial assistance to organisations in the so-called MUSH sector (municipalities, universities, schools and hospitals) that implement energy efficiency projects. Investment-grade audits are conducted by ESCOs, which then enter into a guaranteed savings agreement with the programme's participants.

In the next step, the bond proceeds are used to pay for the construction and installation of the new equipment that will provide the energy efficiency improvements. ESCOs conduct monitoring and verification, seconded by experts who forecast quarterly and yearly performance. These independent forecasts help ensure that the ESCOs do not overestimate the energy savings achieved during the audit process. Once the construction phase has been completed, participating organisations make instalment payments to the SEU, which then assigns these financing payments to a trustee placed in charge of the repayment of the principal and interest on the bonds. Bundling the financing of several large-scale energy efficiency projects into a single bond issue backed by contract performance guarantees can secure much lower borrowing costs than if these projects were financed individually.

3 The SEU model is also in advanced stage of implementation in the State of Pennsylvania; more information can be found at http://freefutures.eg/pennsef/about/.

Figure 7.6 SEU model



* Participant enters into lease with the issuer agreeing to make quarterly payments for installation of energy/water conservation and onsite clean energy generation measures ("CMs").
** Participant signs a Guaranteed Savings Agreement ("GSA"), with a Program pre-qualified Energy Service Company ("ESCO") that identifies all CMs, their annual guaranteed savings and debt service, payback periods, and other metrics over the life of the agreement.
*** Participant and ESCO enter into a Program Agreement and agree to report performance metric search quarter by CM, and to specify direct and indirect job creation.
**** Issuer issues bonds/loans secured by payments under the Participants' Leases.
Source: FREE (2013), http://freefutures.org/genesis/wp-content/uploads/2013/11/2013_FREE-Policy Brief_No-1_SEU-Understanding-Basics.pdf.

Key point *The financing strategy of the SEU utilises different financial, social and institutional levers to accelerate the uptake of sustainable energy options.*

Supporting legislation from national or sub-national (e.g. state) jurisdictions can be instrumental to enabling the success of the SEU model. For instance, national or state governments can make the SEU bonds tax-exempt, meaning that bond subscribers will not have pay any withholding tax on the bond yield.

The IUS model

The IUS model concept was developed in 2014 by the Rocky Mountain Institute (RMI) for Fort Collins Utilities, the municipally owned utility of Fort Collins, Colorado. The city council of Fort Collins recently committed to an ambitious climate action plan, aiming to reduce GHG emissions by 80% by 2030 and to become carbon-neutral by 2050. A new business model for the local utility is considered an important prerequisite for achieving these goals.[4]

The IUS model is based on developing a city energy system that significantly increases electrification of end uses and radically decarbonises the electricity generation mix.

The three pillars of the IUS model are: 1) establish an on-bill financing mechanism that allows customers to make renewable energy upgrades to their homes without high up-front costs; 2) structure the necessary utility service or financing fees to cover the shortfall in utility revenues from declining energy sales to cover operational and fixed costs; and 3) reimagine a utility's energy services department as a profit centre as opposed to a cost of doing business (RMI, 2015).

4 The roll-out of the IUS model in Fort Collins is in its initial stage, with a pilot phase expected to start in early 2016.

At the core of the IUS model is the integration of different products, services and financing instruments. Within a comprehensive package, customers would be offered several energy services, such as energy efficiency improvements, rooftop solar, electrification of transport and heat systems, and demand-side response. These services would be paid for monthly by customers in their utility electricity bill, and the utility would align the services offered with the objective of maintaining financial stability and sustainability (e.g. constant or increasing revenues).

In the first, implementation stage of the IUS model, the utility would contact customers to inform them of the programme, describing the sustainable energy options available. An independent third-party provider would then provide more detailed information about the services that could be adapted to the specific needs of the final customer, followed by audits conducted by contractors. The same contractors would then be in charge of installing the package of sustainable energy options in a streamlined process that would minimise operation costs.

Among the advantages of the IUS model is its ability to build on both the network of existing customers of the utility and its own organisational capacity. Since the change in the business model would be radical, RMI has suggested a gradual transition through a pilot programme, followed by a zonal roll-out to reduce delivery costs for the utility and take advantage of similarities in the approximate building stock (Campbell et al., 2014).

Recommended actions for the near term

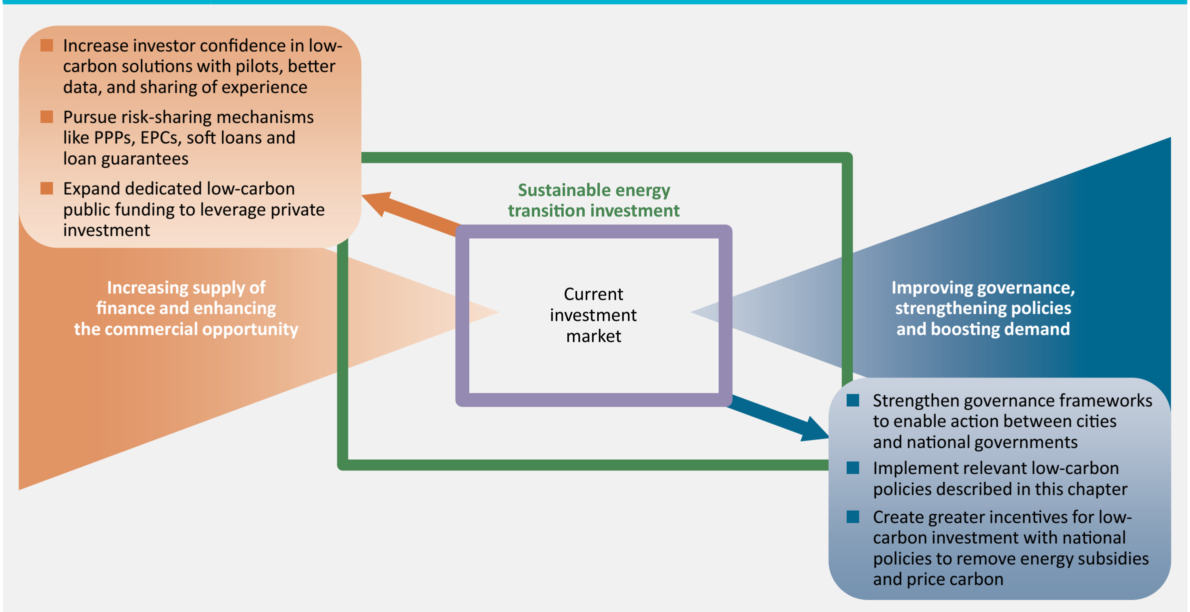
Fulfilling the urban energy potential requires a two-pronged approach to increase the size of financing available and change policies, governance and institutions to promote low-carbon investment (Figure 7.7). The role of all governments to pursue these two ends is integral.

Increasing the pool of finance will require co-ordinated action to broaden the share of private financing and the attractiveness of low-carbon investment. Local and national governments can implement programmes and support mechanisms that build capacity among investors to strengthen the business case for low-carbon investment. Investor confidence increases with greater exposure and experience in low-carbon investments, and the market expands thanks to greater policy stringency and certainty.

Governments need to foster an environment where municipalities are empowered to increase their ambition to support low-carbon actions. This will require devolving legislative powers and fiscal capacity to the appropriate levels of government that will maximise the cost-effective deployment of low-carbon investments. National governments will need to ensure that disincentives to low-carbon investments are changed within their existing policy framework, including reducing energy and GHG emissions subsidies.

Closer linkages between cities and national governments will need to be developed through official and unofficial processes. National governments will increasingly be encouraged to look at cities as tools with which to achieve their national carbon reduction targets, while cities will need to be increasingly responsible to national policies and commitments.

Figure 7.7 Expanding the size of the investments in low-carbon energy



Key point *The market for sustainable energy investment needs to expand by both increasing the demand with policy and governance changes and strengthening the supply of finance by improving investor confidence.*

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Chapter 8

Mexico's Sustainable Energy Transition: The Role of Cities

Mexico is determined to pursue a sustainable energy transition and has demonstrated this intention not only by passing ambitious climate laws and strategies domestically, but also through proactive engagement in international climate negotiations. Cities will have to play a crucial part in achieving the country's ambitions to significantly reduce carbon emissions.

Key findings

- ***Mexico has embarked on an ambitious transition to sustainable energy, with the official goal to reduce carbon dioxide (CO_2) emissions by 50% below 2000 levels by 2050.*** *The* Energy Technology Perspectives *(ETP) 2°C Scenario (2DS) shows that this path not only is achievable, but also can provide other sustainable development benefits to Mexico.*
- ***The greatest contribution to CO_2 emissions reduction in the Mexican 2DS is from the power sector:*** *almost half of the reductions achieved between 2013 and 2050 come from electricity generation, mainly due to an increased deployment of solar and wind power.*
- ***Transport is the second most important sector in terms of potential for emissions reduction.*** *The best options to reduce emissions are more efficient, lower-emission vehicles; increasing trips on public transportation; and a switch to biofuels.*
- ***The share of the urban population in Mexico is continuing to grow: in 2010, 73% of Mexicans lived in cities; in 2020 this share is expected to rise to 83%.*** *The degree of success of Mexico's sustainable energy transition will greatly depend on how energy use evolves in cities – namely on how houses are built and on residents' mobility choices in urban areas in the future.*
- ***Mexican cities account for about 50% of the country's transport final energy demand and 70% of buildings final energy demand in 2013,*** *and would have even larger shares in the 6°C Scenario (6DS) by 2050. In the 2DS, more than half of emissions reduction opportunities would be achieved in the urban buildings and transport sectors.*
- ***For decades, the lack of a national policy framework on urban development has impeded the systematic adoption of sustainable urban energy consumption patterns.*** *Urban sprawl in the 1980s has left a legacy of carbon-intensive urban infrastructure.*
- ***The increase in transportation distances to urban centres has resulted in***

congestion, productivity losses and a lower level of well-being. *However, infrastructure planning in Mexico is still largely dominated by car-centred thinking.*

- ***The incorporation of distributed energy generation systems will help the transition to sustainable cities, consolidating a way for Mexico to meet national clean energy targets.*** *The installation of solar roof-top systems, waste-to-energy plants and co-generation systems are part of the solution of an integrated, efficient and clean energy supply in cities.*
- ***Solar photovoltaic (PV) systems could meet 16% of urban electricity demand in Mexico by 2050;*** *leveraging this potential will require integrated policy, market and regulatory frameworks.*

Opportunities for policy action

- *Mexico's decarbonisation objectives are achievable if a stable and effective policy framework is implemented, and particularly if Mexican cities are enabled and incentivised to effectively pursue sustainable energy transitions.*
- *This effort should foster a more effective vertical integration of all levels of government to address divergence in objectives among federal, state and local governments as well as addressing the lack of human resources and funding, and information asymmetries in cities.*
- *Reversing the impacts of decades of urban sprawl and avoiding future sprawl will require co-ordination across all policy-making levels to advance integrated land-use and transportation planning.*
- *Mexico should build on its experience with cross-cutting and financing mechanisms, such as the* Fondo Metropolitano *and the Environmental Commission of the Megalopolis (*Comisión Ambiental de la Megalópolis *[CAMe]), to promote integrated and well co-ordinated planning.*
- *Promotion of retrofit in existing buildings and enforcement of building codes can support greater energy efficiency. The federal government can set national standards, but implementation depends on municipal governments that must monitor the progress and that need adequate capacity for enforcement, training and information.*
- *Metropolitan areas in hot climates and with high demand for social housing should set an example by building sustainable social housing, which can help build local capacity and supply chains for implementation of more rigorous building codes in the construction sector.*
- *A more effective vertical integration among different levels of government is also needed to foster the competitiveness and attractiveness of public transport networks.*
- *A deliberate attempt should be made to steer priorities towards public transport and low-carbon options, taking into account urban energy sustainability objectives.*
- *Car use can be discouraged by establishing or raising parking charges in central areas, while enhancing efficiency of the public transport system and integrating car use with other forms of transport. Local governments can facilitate mobility schemes such as car-sharing and pooling to improve efficiency for commuters.*
- *Several elements of integrated land-use planning are already in place at different levels of administration. To achieve the urban energy transition, existing approaches need to be enhanced and turned into effective nationwide planning tools.*
- *Active participation of public and private actors is necessary for the implementation of smart-grid technologies in cities. Boosting the integration of renewable energy will help to meet national targets and it will enhance the liveability of Mexican cities.*

Mexico's sustainable energy transition and the *ETP 2DS*

Mexico has embarked on an ambitious transition to sustainable energy. Its outcome will greatly depend on how clean energy policies are implemented at different levels of governance. This chapter analyses the potential role for Mexican cities in implementing the energy transition.

Building on the *ETP 2012* regional spotlight on Mexico, this chapter provides a revised assessment of the Mexican 2DS[1] over the period to 2050. The chapter includes an analysis of different carbon reduction options underpinning the opportunities for a national transition to a low-carbon energy system. In line with the topical analysis of *ETP 2016*, the analytical scope is widened with an analysis of the technology deployment opportunities and behavioural shifts that need to take place at the urban level. This analysis is framed within a broader policy analysis addressing which national and local policies are needed to cost-effectively realise this transition relative to a scenario based on current and planned policies. Another aspect discussed in the chapter is how a more effective alignment of Mexican national and local policies can contribute to efficiently achieving national objectives of the sustainable energy transition.

Mexico's commitment to sustainable development has its roots in climate change policies, starting with Mexico's incorporation to the United Nations Framework Convention on Climate Change (UNFCCC) in 1993 and its ratification of the Kyoto Protocol in 2000. The country's vulnerability to climate change is evidenced by the large social and economic impact of extreme weather events that have occurred in recent history. Between 2000 and 2011, drought, flooding and cyclones were responsible for about 5 000 casualties, affected 13 million people and resulted in economic losses of around 250 billion Mexican pesos (MXN) (USD 15 billion) (PNDU, 2013).

Against this background, the country has become very active in international climate policy, not least by hosting the 16th Session of the Conference of the Parties to the UNFCCC in 2010. In recent years, the Mexican Congress has passed a climate change law (2012), which mandates a reduction of CO_2 emissions by 50% below 2000 levels by 2050. Furthermore, the law stipulates that 35% of the country's electricity should come from clean energy sources by 2024. Mexico has also published the *Special Climate Change Programme (PECC) 2014-2018*, outlining actions to reduce the vulnerability of population, ecosystems and productive sectors to climate change and increase resilience in strategic infrastructure. The implementation of the programme is co-ordinated by the Environment Ministry (*Secretaría de Medio Ambiente y Recursos Naturales* [SEMARNAT]), under the guidance of an Inter-Ministerial Commission on Climate Change. The total reduction of greenhouse gas (GHG) emissions to be realised by the implementation of PECC mitigation actions is estimated between 83 and 96 million tonnes of carbon dioxide equivalent ($MtCO_2$-eq) per year. The country has also introduced a carbon tax on fossil fuels (excluding natural gas), and in March 2015 was the first emerging economy to submit its Intended Nationally Determined Contribution (INDC) to the UNFCCC, proposing to unconditionally reduce its emissions of GHGs by 22% below baseline emissions in 2030 (Gobierno de la Republica, 2015).

1 The Mexican 2DS is a representation of the evolution of the Mexican energy system consistent with the global 2DS, which aims at keeping global emissions within a limit that would ensure a 50% probability of keeping the long-term increase of global temperatures within 2° Celsius. In that respect, the extent to which domestic energy-related carbon emissions are reduced and the contribution of the different sectors and technologies to such reduction are not defined on a normative basis or from expert-based judgements but are determined through a cost-optimisation process carried out by the *ETP* model. The *ETP* 2016 scenarios are described in Chapter 1, Box 1.1.

As a major oil-exporting country, Mexico's energy sector is central to its climate policy and transition to a sustainable development model. Until recently, the country's energy mix still included large amounts of fuel oil for power generation. With the availability of low-cost natural gas from the United States, this usage has started to change, with the share of fuel oil in the electricity mix dropping from 32% to 15% since 2003, while natural gas surged from 34% to 52% in the same time frame. Overall, Mexico today stands at 21% clean energy power generation, with hydropower (13%) and nuclear (3%) contributing the greatest amounts. Despite their huge potential, non-hydro renewable energies still accounted for only 4% of electricity generation in 2013, mostly geothermal and wind (SENER, 2015).[2]

In addition to climate considerations, Mexico's impulse for an energy transition stems from a need to reduce air pollution as well as considerations of energy security. In view of Mexico's ambitious sustainable energy goals, effective energy policies in cities will be crucial. Urban residents account for 71.6% of the population (PNDU, 2014), and by 2020, that share is expected to rise to 83.2% (72.4 million people). How these people's energy supply will be ensured, how their houses will be built and how they will move around their cities will play a large role in determining the success of Mexico's energy transition.

Cities could be critical in the decarbonisation of power supply, insofar as they provide dense markets for the deployment of clean energy technology such as rooftop solar systems for heat and power generation, electric vehicles (EVs) for transportation, and waste-to-energy (WTE) schemes. Building codes can help ensure the sustainability of future additional building stock. Integrated land-use planning can contribute to minimising transport needs and facilitating the development of local economies.

A 2DS for Mexico

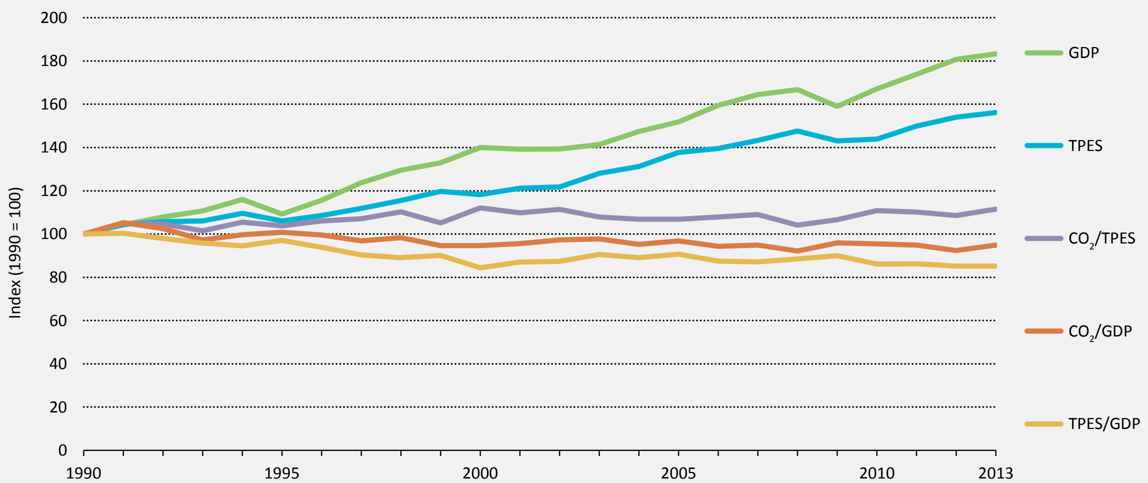
Mexico is among the world's 15 largest countries in terms of gross domestic product (GDP), population and geographic area. Its economic and political traction in the international arena is expected to increase significantly in the coming decades. The latest trends in the Mexican energy system reflect strong economic growth, a demographic transition and a shift in the composition of the economy towards reduced reliance on oil exports and energy-intensive industries (Figure 8.1).

Energy demand

Primary energy demand totalled about 8 exajoules (EJ) in 2013, making Mexico the world's 13th-largest energy consumer and Latin America's second-largest energy consumer. Despite having already reached a peak in oil production and exports in 2005, Mexico is still among the largest oil exporters in the world, with oil export revenues contributing about a third of the federal budget. With a 53% share of primary energy supply, oil also plays a dominant role in the Mexican domestic energy system (Figure 8.2). The share of oil in primary energy supply is significantly higher than other countries with similar GDP per capita and human development index levels. This high share of oil is a result not only of Mexico's status as an oil producer but also of its refining activity and of structural elements within the transport end-use sector (see following section on "Transport energy use"). In addition, though domestic heavy-fuel oil consumption has decreased in the last few years, heavy-fuel oil still accounts for more than 15% of the fuel mix for power generation (compared with an average share of 5% for Organisation of Economic Co-operation and Development [OECD] economies).

2 Since 2013 the government has launched a series of energy technology research and development (R&D) centres to help spur the deployment of bioenergy, geothermal, ocean, solar and wind energy.

Figure 8.1 **Mexico's historic GDP, primary energy supply and carbon intensity**



Note: TPES = total primary energy supply. Figures and data that appear in this report can be downloaded from www.iea.org/etp2016.
Source: IEA (2015a), *IEA World Energy Statistics and Balances* (database), www.iea.org/statistics.

Key point *While Mexico's energy supply has become more emissions-intensive, the economy has become less energy-intensive.*

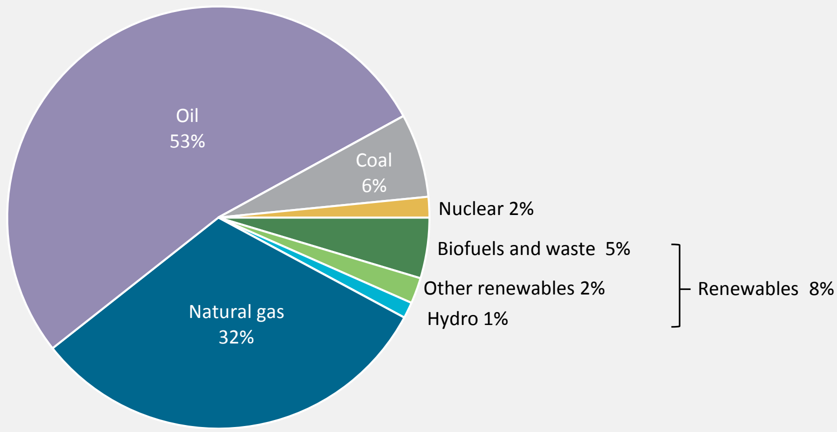
Another distinctive feature of Mexico's primary energy supply is the important role played by natural gas, which contributes 32% of primary energy supply and 56% of power generation. The prominent part played by natural gas and oil in power generation contributes to a relatively low share of coal (6%) in primary energy supply, owing to its limited contribution to power generation (12% of the fuel mix for power). Overall, fossil fuels meet about 90% of primary energy demand, with the remaining share divided between nuclear (2%) and renewables (8%).

The sector with the largest share of final energy demand is transport (45%), followed by industry (29%) and buildings (17%). The low share of the buildings sector relative to the OECD average (31%) can be explained by the modest demand for heat as an end-use service, because of favourable climatic conditions. Conversely, the higher share of transport compared with the OECD average (35%) is a result of the relatively high use of personal transport modes and the relatively low efficiency of personal vehicles.

Due to the expected strong economic growth, as well as continued urbanisation, primary energy demand is projected to almost double over the period 2013-50, reaching about 16 EJ in the 6DS scenario (i.e. business as usual). In these baseline projections of the 6DS, fossil fuels will continue to have a dominant role, contributing 84% of primary energy supply. One of the consequences of the large increase in primary energy demand and the continued dependence on fossil fuels will be a 95% increase in energy-related carbon emissions, which are projected to grow from 478 million tonnes (Mt) to 930 Mt by mid-century. Such an increase in CO_2 emissions is not consistent with the long-term sustainability goals of the Mexican federal government.

If more ambitious and effective policies are put in place to achieve greater decarbonisation in line with the global 4DS, the absolute growth by 2050 in primary energy demand and energy-related CO_2 emissions could be reduced by 30% and 65%, respectively. The relatively higher reduction in carbon emissions is explained by a larger role of non-fossil fuels in the primary energy mix by 2050, increasing to 30% (from 16% in the 6DS).

Figure 8.2 Mexico's TPES in 2013



Source: IEA (2015a), *IEA World Energy Statistics and Balances* (database), www.iea.org/statistics.

Key point *Mexico's primary energy supply is dominated by fossil fuels.*

In the Mexican 2DS, primary energy demand would grow to about 11 EJ by 2050, with a one-third increase from 2013 levels. Energy-related carbon emissions are reduced by about 220 Mt (55% reduction) relative to 2013 levels, reaching about 260 Mt by 2050. The sectors that show the largest reductions in annual emissions by 2050 in the Mexican 2DS are other transformation processes (e.g. refineries) (-84%), power (-70%) and buildings (-49%). Carbon emissions from transport would be reduced by almost one-third, but the reduction in absolute levels (-50 Mt between 2013 and 2050) would be the second largest after power (-104 Mt) (Figure 8.3). In terms of the low-carbon technology mix required to achieve the emissions reduction in the Mexican 2DS, the main differences relative to the global 2DS are the bigger role played by renewables and end-use fuel switching, whereas a less significant contribution from carbon capture and storage (CCS) and nuclear is projected in Mexico.

Energy use in Mexican cities will see a significant increase as a result of urbanisation and increasing urban economic activity. Urban GDP per capita in Mexico is projected to grow from USD 19 600[3] in 2013 to USD 40 300 in 2050,[4] whereas according to United Nations Department of Economic and Social Affairs (UN DESA) projections, urban population will grow from 96.3 million to 134.8 million over the same time frame. As a result, urban GDP in absolute terms would almost triple, reaching USD 5.5 trillion in 2050. Final energy consumption from urban buildings and transport activity in Mexican cities will obviously grow in parallel with demographic and economic drivers, increasing from about 1.8 EJ in 2013 to 5 EJ in 2050 under the 6DS. In the urban 2DS for Mexico, the deployment of energy-efficient technologies and greater energy conservation in urban buildings and transport systems lead to a 40% reduction in final energy use relative to 6DS levels. Higher energy-savings and increased use of low-carbon fuels in urban buildings and transport final uses are reflected in a reduction of about 120 Mt

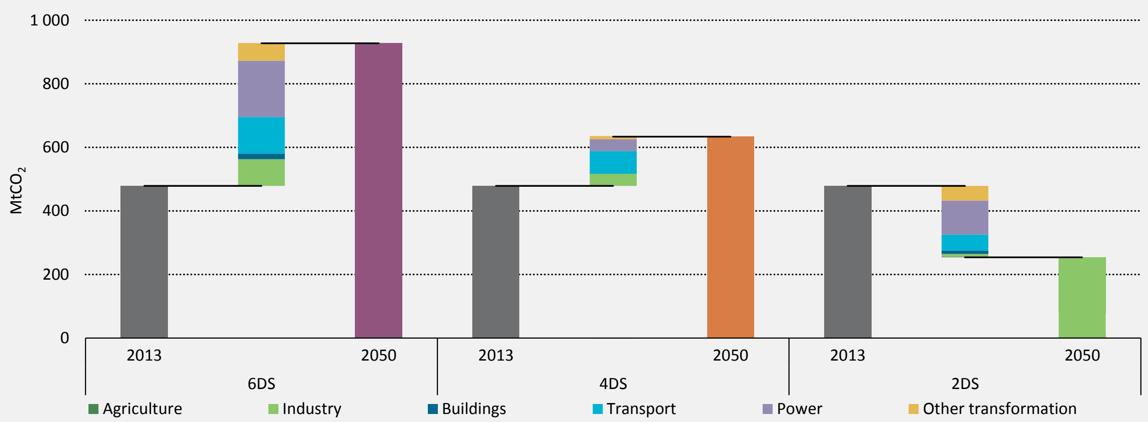
3 Unless specified otherwise, USD figures are in purchasing power parity in constant 2014 terms.

4 Urban GDP was estimated for 189 countries from 2013 to 2050 using McKinsey (2015), McKinsey Global Institute Cityscope v2.55; IMF (2015), *World Economic Outlook Database, April 2015*, www.imf.org/external/pubs/ft/weo/2015/01/weodata/index.aspx; and IEA (2015d), *World Energy Outlook*.

(more than half of the total reduction that would be achieved in the 2DS) in energy-related carbon emissions by 2050.

The following sections discuss in greater depth the Mexican 6DS and 2DS in the power generation sector as well as in the three main end-use sectors – transport, industry and buildings.

Figure 8.3 Contributions of sectors and technologies to Mexico's carbon emissions reduction in the 2DS



Key point *The power generation and transport sectors are essential to the Mexican 2DS.*

Power generation

Electricity generation reached 297 terawatt hours (TWh) in 2013 and would more than triple by 2050 in the 6DS. Natural gas would continue to dominate the power fuel mix, with its share slightly increasing from 56% to 63%, but the consumption of this fuel in absolute terms for generating power would more than triple. The share of coal would also increase, whereas oil's contribution to electricity generation is projected to gradually decrease to zero by 2050. The growth in carbon emissions from power generation is lower than that of electricity demand, because of the more efficient conversion of natural gas and the uptake of renewables. However, CO_2 emissions from coal and natural gas power plants would almost double, reaching 333 Mt by 2050 in the 6DS.

In the 2DS, the Mexican power sector is almost fully decarbonised by 2050. To cut power sector CO_2 emissions by 70% would be a major challenge for Mexico, and would require an enormous scale-up of renewable energy (mostly wind and solar), as well as the integration of CCS with a portion (12 gigawatts [GW]) of the operating natural gas and coal power capacity (51 GW) by 2050. Furthermore, an increased share of nuclear energy is considered under the 2DS. Co-generation[5] is another effective option to decarbonise power generation in industrial plants. Renewable energy sources can also contribute to an ambitious low-carbon transition in the Mexican power sector. For instance, solar PV and concentrated solar power (CSP) could contribute 29% of total electricity generation by 2050 in the 2DS, with onshore and offshore wind contributing 19%. About 90% of the total generation from PV systems in the 2DS in 2050 (120 TWh) would be used to meet a significant part (16%) of electricity demand in cities.

5 Co-generation refers to the combined production of heat and power.

Transport energy use

Final energy consumption in the transport sector totalled 2.5 EJ in 2013, making up 45% of total final energy use. This share, among the highest among member countries of the OECD, can be explained by a legacy of low fuel costs and the relatively easy access to car ownership, partly due to the cross-border flow of used vehicles from the United States. As a result, the share of personal light-duty vehicles in transport activity (passenger-kilometres) among all transport modes is also quite high: 78% versus an OECD average of 65%. Without a strong policy intervention to increase fuel efficiency, final energy demand in transport is projected to increase by about 80% from 2013 levels, reaching 4.2 EJ by 2050 in the 6DS.

In the 2DS, final energy demand in the transport sector is projected to peak shortly before 2030 and then start decreasing, bringing demand in 2050 below the level of 2013. The share of oil in transport will also be reduced to less than two-thirds from the current level (about 98%), with electricity, biofuels and natural gas collectively reaching 35% of the fuel mix. The factors contributing to this structural change are more stringent fuel economy standards for passenger light-duty vehicles, the expansion of public transport fostered by strong local-level travel demand management and compact city policies, as well as favourable fiscal regimes for low-carbon fuels. These options would make it possible to achieve a 50% decrease in carbon emissions in the transport sector in 2050 relative to the 6DS.

Urban transport systems are strategic for achieving energy sustainability, not only within the national transport sector but for the overall sustainability of the Mexican energy system. Total final energy consumption from urban transport reached 1.3 EJ in 2013 (about 50% of total final energy demand for transport at the national level), and would increase by 80% over the time frame 2013-50 in the 6DS. Reduced demand for urban mobility, a shift to public transport and deployment of low-carbon vehicles in cities would reduce transport final energy demand by 50% relative to the 6DS levels by 2050. Efforts on this front are needed because, despite efforts over the past three decades to improve air quality in the country's 67 priority atmospheric basins, 72.2 million people live exposed to poor air quality (SEMARNAT, 2014).

Industrial energy use

With about 1.4 EJ of energy consumption, industry accounted for almost 30% of total domestic final energy use in Mexico in 2013. The five most energy-intensive sectors (chemicals and petrochemicals, iron and steel, cement, pulp and paper, and aluminium) make up about 48% of industrial final energy consumption, for which oil and natural gas are the vectors with the highest shares. The food and tobacco sector represents almost 7% of overall industrial energy consumption, a greater share than pulp and paper and aluminium together. Industrial final energy consumption would almost double to 2.7 EJ in 2050 in the 6DS, driven by an increasing demand for industrial materials, with coal and natural gas increasing their shares of the total energy mix.

As a result of energy efficiency improvements, the adoption of best available technologies (BATs) and resource efficiency measures, the 2DS considers a much more modest increase (23%) in final energy consumption in the industrial sector, even accounting for similar materials demand growth, totalling about 1.7 EJ in 2050. The almost 60% reduction in annual direct carbon emissions from industry in 2050 in the 2DS compared to the 6DS would mainly result from the following strategies: switching to lower-carbon fuel and feedstock mixes (with coal use almost disappearing); the introduction of innovative process technologies, including CCS with almost 8 million tonnes of carbon dioxide ($MtCO_2$) captured and stored in 2050; and an increased electrification of low-temperature processes.

Buildings energy use

Final energy use in the buildings sector totalled about 1.3 EJ in 2013, accounting for one-quarter of total final energy consumption and about 5% of total direct CO_2 emissions. The largest end uses are water heating (36%), appliances (13%) and cooking (12%), with space heating and cooling accounting for 11% and 9% of total buildings final energy demand, respectively. Lighting and other miscellaneous end uses (e.g. office equipment) account for the remaining 20%. Electricity and oil products (mostly liquefied petroleum gas for water heating and cooking) are the most common fuels used to meet end-use demand. Traditional use of biomass, typically for water heating and cooking, also accounts for an important share (roughly 33%) of final energy consumption in residential buildings, although this has been decreasing steadily over the last three decades (in share and absolute consumption) as households continue to shift away from biomass with increasing income and access to electricity and other commercial fuels.

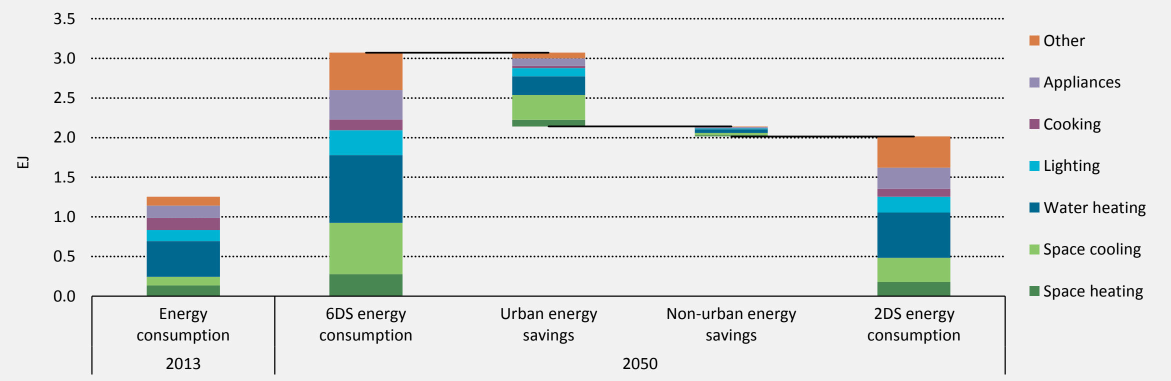
Final energy consumption in the buildings sector in the 6DS would nearly triple from 2013 levels, reaching about 3.1 EJ in 2050, with resulting direct sectoral CO_2 emissions also increasing to 32 Mt in 2050. The most important factor behind this marked growth in final energy is increasing GDP per capita, which will lead to a lower number of people per household and greater floor space per person, driving up the total number of households and building floor area significantly. Cooling demand in the 6DS would increase more than fivefold from 2013 levels.

In the 2DS, final energy use from buildings would still increase by roughly 60%, reaching about 2 EJ in 2050, whereas direct CO_2 emissions are more than halved relative to 2013 levels. Electricity is the dominant fuel for end uses, meeting 75% of buildings' final energy consumption. Solar thermal is also projected to make an important contribution to the fuel mix in the 2DS, meeting about 10% of end-use demand by 2050. The reduction in the projected growth rate compared with the 6DS will need to be driven by effective policy action through stronger building energy codes, rigorous energy efficiency standards for end-use technologies, and the phase-out of inefficient technologies, such as incandescent and halogen lamps for high efficiency technologies, such as light-emitting diodes (LEDs).

Cities accounted for about 76% (0.9 EJ) of total final energy demand from the buildings sector in Mexico. In the 6DS, characterised by the absence of new policies to reduce energy use, final energy demand would reach about 2.7 EJ in 2050. This tripling in demand is largely the result of space cooling demand and growing demand for appliances and other electrical plug loads from urban households and businesses. Sustainable energy options for buildings would apply to both urban and rural energy systems. However, in urban settings, more efficient building envelopes as well as increased electrification (e.g. heat pumps) can find the market niches required to reach those thresholds that can provide significant economies of scale, which would be reflected in lower costs.

In the 2DS, final energy demand from urban buildings by 2050 could be reduced by more than one-third (1.7 EJ) relative to the 6DS. This energy efficiency potential that can be unlocked from urban buildings amounts to 90% of the total reduction in buildings energy demand in Mexico in the 2DS.

Figure 8.4 Energy savings in the Mexican buildings sector, 6DS to 2DS



Key point *Efficient water heating, space cooling and heating, and appliances are the major contributors to emissions reduction in the Mexican buildings sector.*

Relevance of cities for national sustainable development

Mexico has experienced rapid urbanisation in the last 20 years, moving from 50% of the population living in cities in 1978 to 71.6% in 2010 (Table 8.1) (UN Habitat, 2011; INEGI, 2015). The urban population share will continue growing in the future, although at a slower pace, reaching 83.2% by 2020 (PNDU, 2014).

Urban population is generally associated with higher relative wealth, which in turn is associated with higher energy consumption. In Mexico this correlation translates to almost double the average energy consumption per capita in cities as compared with rural areas (Sanchez Peña, 2012). Mexico's cities also face inherent challenges due to their urbanisation model based on low density and developments far from city centres. In fact, Mexican cities register the third-highest level of sprawl among OECD countries (OECD, 2015a).

Many Mexican cities will not be able to face by themselves the transition to sustainable urban energy supply and more efficient growth patterns. To avoid sprawl in new developments and to promote densification in developed cities, a national policy framework is needed that fosters efficient buildings and public transport.

The roots of the current challenges are found in Mexico's rapid urbanisation process. This process started in 1991 with the constitutional reform of Article 27, which allowed the sale of communal land surrounding cities, the so-called *ejidos*.[6] This legislation put on the market a large area of relatively cheap land for real estate development on the outskirts of major cities. To reduce the housing deficit, the public fund for housing *Instituto del Fondo Nacional de la Vivienda para los Trabajadores* (INFONAVIT) provided financing for massive housing development programmes. This initiative was effective in reducing the housing deficit, reducing by 3 million people the number of Mexicans living in "overcrowded" conditions and reducing the average occupancy rate per room from 2.6 people to 2.0 people (PNV, 2014).

6 *Ejidos* are publicly owned lands whose usage rights belong to a collective or individual.

This situation triggered the construction of mostly low-density new urban developments. Moreover, urbanisation has fostered the development of "metropolitan areas".[7] The resulting massive urban growth was carried out without proper planning and co-ordination among municipalities (OECD, 2015a; PNV, 2014). The increased distances between homes and workplaces result in congestion, productivity losses and a lower level of well-being (OECD, 2015a; SIF, 2015).

Table 8.1 Mexico's metropolitan areas with more than 500 000 inhabitants

Metropolitan area	Total municipalities	Federal state	Population 2010	Average growth 2000-10 (%)	Average urban density (inhab./Ha)
Valle de México	76	Distrito Federal-México	20 116 842	0.9	160.1
Guadalajara	8	Jalisco	4 434 878	1.8	124.4
Monterrey	13	Nuevo León	4 106 054	1.9	109.1
Puebla-Tlaxcala	39	Puebla-Tlaxcala	2 728 790	1.8	76.6
Toluca	15	México	1 936 126	2.2	64.8
Tijuana	3	Baja California	1 751 430	2.5	85.0
León	2	Guanajuato	1 609 504	2.3	125.9
Juárez	1	Chihuahua	1 332 131	0.9	67.9
La Laguna	4	Coahuila-Durango	1 215 817	1.8	77.1
Querétaro	4	Querétaro	1 097 025	2.9	98.1
Soledad de Graciano Sánchez	2	San Luis Potosí	1 040 443	2.0	105.9
Mérida	5	Yucatán	973 046	1.9	58.0
Mexicali	1	Baja California	936 826	2.0	59.3
Aguascalientes	3	Aguascalientes	932 369	2.4	104.9
Cuernavaca	8	Morelos	924 964	1.4	70.7
Acapulco	2	Guerrero	863 431	0.8	98.0
Tampico	5	Tamaulipas-Veracruz	859 419	1.4	80.5
Chihuahua	3	Chihuahua	852 533	2.0	65.9
Morelia	3	Michoacán	829 625	2.0	92.5
Saltillo	3	Coahuila de Zaragoza	823 128	2.5	81.3
Veracruz	5	Veracruz	811 671	1.6	104.6
Villahermosa	2	Tabasco	755 425	2.2	85.2
Reynosa – Río Bravo	2	Tamaulipas	727 150	3.2	70.6
Tuxtla Gutiérrez	3	Chiapas	684 156	2.6	82.3
Cancún	2	Quintana Roo	677 379	4.5	103.2
Xalapa	7	Veracruz	666 535	1.8	96.7
Oaxaca	22	Oaxaca	607 963	1.9	64.3
Celaya	3	Guanajuato	602 045	1.9	86.1
Poza Rica	5	Veracruz	513 518	0.9	63.4
Pachuca	7	Hidalgo	512 196	3.1	76.3

Note: Ha = hectare.
Sources: INEGI (2015), "Sistema Estatal y Municipal de Bases de Datos"; CONAPO (2013), "Delimitación de las zonas metropolitanas de México 2010".

7 In 2012, the Mexican government, the National Council for Population (CONAPO) and the National Statistics Institute (*Instituto Nacional de Estadistica y Geografia* [INEGI]) published for the first time a list of the metropolitan areas in Mexico. The latest update identified 59 metropolitan areas formed by 367 municipalities. In total, 63.8 million people, 56.8% of the Mexican population, live in these metropolitan areas.

Challenges and opportunities of Mexican cities

Urban buildings sector in Mexico

From 1990 to 2010, the population living in metropolitan areas in Mexico rose by 20.5 million people, while the metropolitan area grew by 20.6%. This growth resulted in a reduction of the average urban density from 124 inhabitants/Ha to 111.5 inhabitants/Ha. In addition, rapid urbanisation occurred without appropriate planning (PNV, 2014) and largely without consideration of energy-efficient construction standards. Today, the residential sector represents 4% of the direct GHG emissions in Mexico, while the cement, iron and steel industries – directly linked to construction – account for another 9%. Projected construction of buildings over the coming decades represents a tremendous challenge for the national objectives in sustainable development. CONAPO estimates that the number of houses will rise from 28.6 million (2010) to 43.7 million by 2050, not only because of growing population, but also as a result of the reduction of the number of inhabitants in each house.[8] In addition, although improvements in terms of the housing stock quality have been achieved, energy sustainability criteria are only beginning to be taken into consideration in national planning and implementation of housing programmes. Improvement in building standards could promote standardisation of more sustainable construction methods. But for more demanding and assertive building standards to have an impact, several improvements to the technical, managerial and financial capacities of small cities will need to be realised. Federal and state governments could lead this process, through specialised capacity-building programmes and funding mechanisms, and indeed Mexico has taken initial steps by defining Official Mexican Standards (Normas Oficiales Mexicanas [NOMs]) and tax incentives, including at the state level.

Changes in energy demand patterns will also play an important role in Mexico through 2050. Air-conditioning penetration is still low at 13% (Davis and Gertler, 2015). Given the country's warm climate, space cooling demand will increase rapidly, driven by increasing wealth. More energy-efficient construction methods will be essential for new building development, and promotion of more efficient technologies will be needed in the existing housing stock.

Without concerted effort to reduce energy consumption in buildings in Mexico, total annual GHG emissions from residential and services buildings are likely to more than double in the 6DS. This total does not include non-GHG emissions, such as local air pollutants and hazardous fumes, from traditional biomass use in residential cooking and heating. The bulk of these savings comes from decarbonisation of the electricity sector, where emissions reduction from final energy consumption in buildings accounts for the remaining emissions savings in the 2DS. More efficient water heating, space cooling and heating, and appliances are the major contributors to emissions reduction.

Policies to reduce the energy used for cooling include product standards and labelling and the promotion of high-efficiency cooling equipment, improvements of thermal envelopes, and measures to foster behavioural changes reducing the need for cooling. Work by the International Energy Agency (IEA) and the Mexican Ministry of Energy (SENER) has identified a number of technology options for Mexico, depending on the area of implementation, potential impact and technological level.

8 Between 1990 and 2010, the number of inhabitants/house fell from 5.1 to 3.9.

Policies will be required to increase the efficiency of appliances, but the need for cooling and heating also has to be reduced. A study jointly conducted by the IEA and SENER analysed the available technology options (Table 8.2). The study produced a strategic framework for space cooling and building code enforcement that aims to address the future issues that could result in increased space cooling energy use and the current challenges with building regulation. Different policy and technology alternatives are clustered according to their potential impact and area of use.

Table 8.2 Examples of building technology options for Mexico

	Residential		Services
	Social housing	**Mid- to high-income**	
Policies for immediate impacts	Weatherisation Quick install measures*	Energy audits Quick install measures	No-cost, low-cost measures Energy disclosure
Policies for long-term energy efficiency	nZEB as an investment	nZEB as an investment	nZEB
Low-tech technologies	Air sealing Insulation Window film Shutters Overhangs Fans	Air sealing Insulation Duct sealing Shutters Overhangs Fans	Insulation Duct sealing Overhangs Fans Cool roof
High-tech technologies	Low-e windows** Programmable thermostat Smart meter	Low-e windows Programmable thermostat Smart meter AC inverter/heat pump	Energy management system Low-e windows Dynamic glazing

* Quick install measures can include easy-to-install measures common in most buildings, such as lighting, air sealing, easy-to-access insulation, window films, shading, thermostats, etc. ** Low-e, film-coated windows and other advanced windows offer increased thermal resistance and reduced solar heat gain.
Notes: nZEB = near-zero energy building; low-e = low-emissivity; AC = air conditioner.
Source: IEA (2015b), *Strategic Framework: Space Cooling and Building Code Enforcement in Mexico*.

Mexico's Climate Change National Strategy (ENCC, 2013) calls for a transition towards low-carbon buildings through "promoting the strengthening, adoption and implementation of regulations, standards and laws to foster technologies for energy, water and gas efficiency and saving". To reduce the average energy demand of the new residential developments needed for the population and economic growth in Mexico for the next decade, the National Energy Strategy 2013-2027 proposed that "standardisation should continue contributing to improve the efficiency standards in vehicles and domestic, commercial and industrial appliances" and calls for "strengthening the implementation of efficiency standards and construction guidelines". An IEA assessment of the level of readiness of Mexican building envelope policy highlights energy subsidies, voluntary programmes and areas for improvements (Table 8.3).

Mexico's National Development Plan also includes the need for social inclusion as a key element of its housing policy. According to the National Council for the Evaluation of the Social Development Policy (*Consejo Nacional de Evaluación de la Política de Desarrollo Social*), 46.2% of the population was living in poverty conditions in 2010 (PND, 2013). Mexico has made significant progress with its social housing programmes, reducing the number of houses without basic services from 44% in 1990 to 19% in 2010 (PND, 2013). However, some areas such as Acapulco and Poza Rica have as much as 30-35% of the population without access to housing, and demand for new houses will continue being high (CONEVAL, 2010). Therefore, social housing programmes could be an ideal starting point for implementing stricter building codes and sustainable energy solutions.

Table 8.3 IEA's assessment of Mexican current buildings envelope policy

Policy aspect	Assessment
Governance	Medium: Shared responsibility between construction and energy departments.
Energy prices	Low: Subsidies in place or below market prices.
Infrastructure and human capacity	Medium: Ability to test some products and university expertise.
Commodity of efficient materials	Medium: Some products are widely available and cost-effective.
Voluntary programmes	Low: Limited to a few demo projects without lasting impacts.
Mandatory building codes	Medium: Mandatory building codes are in place but lack implementation.

Source: IEA (2013), *Technology Roadmap: Energy Efficient Building Envelopes.*

Mexico's climatic conditions are another important variable to consider for sustainable buildings policies because these conditions directly determine cooling and heating needs. Plotting the need for social housing and cooling against each other identifies those metropolitan areas in Mexico that should be encouraged to incorporate sustainability aspects into their social housing (Figure 8.5). As an example, metropolitan areas such as Acapulco and Poza Rica have a high proportion of inhabitants without access to adequate housing, and at the same time these areas are located in air-conditioning intensive zones. These areas should implement more efficient buildings to reduce the need for cooling. In addition, they should strive to increase the efficiency of the electric appliances installed in social housing, serving as an example for others and reducing the electricity bills of the inhabitants.

Building codes as key to a sustainable residential sector

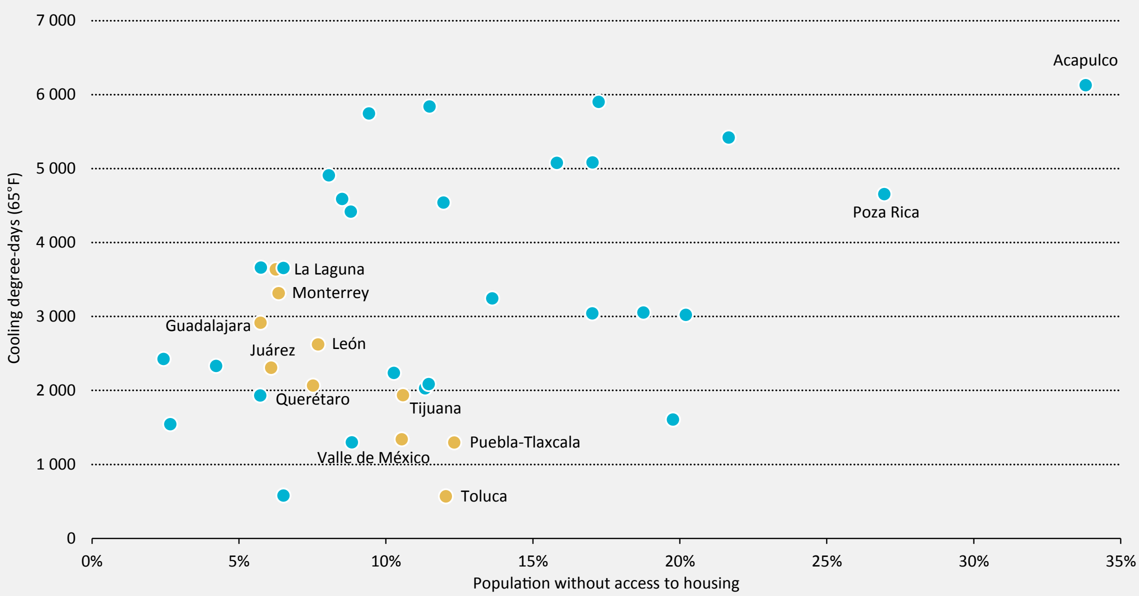
Building codes can play an important role in fostering the introduction of more efficient construction materials and technologies. The Mexican federal government is in charge of developing new building codes through the elaboration of the mandatory NOMs and voluntary Mexican Standards (*Normas Mexicanas* [NMXs]).[9] Municipalities are then in charge of their adoption, implementation, enforcement and monitoring processes. In some cases, local governments may lack technical and financial capabilities to carry out these activities. They may also fear that the enforcement of more efficient building codes may discourage new real estate developments. Loss of such developments could have a large impact on their municipal budgets, which depend on property taxes, construction licences and permits, which INEGI has established in a range between 24% and 50% (IEA, 2015b).

Although space cooling still represents only about 4% of total household energy consumption, space cooling demand is expected to grow rapidly in the near future. Increasing wealth will result in an increase of air-conditioner saturation, from currently about 15% to levels closer to the 95% penetration rates in regions of the United States with similar climatic conditions. Additionally, previous experiences in countries such as the United States suggests that population growth may concentrate in hot climate areas. Finally, one also needs to consider the influence of climate change in increasing temperatures and the addition of new personal electronic devices that generate heat as a by-product (IEA, 2015b).

9 According to a recent study by the *Comisión Nacional de Uso Eficiente de Energía* (CONUEE), the NOMs applied in the residential sector achieved total savings of 11 782 GWh in 2014 (de Buen, Hernández and Naverrete, 2016).

To address these challenges, the IEA and SENER have worked together on the Strategic Framework: Space Cooling and Building Code Enforcement in Mexico. This framework includes a number of recommendations in terms of governance, capacity building, and policies and programmes, as summarised in Table 8.4.

Figure 8.5 **Housing and cooling needs in selected Mexican metropolitan areas**



Note: The ten most populous metropolitan areas are highlighted in orange.
Source: Data on access to housing from CONEVAL 2010, average cooling days from CONUEE 2015.

Key point *Metropolitan areas in hot climates and with high demand for social housing should set an example by building sustainable social housing.*

Integrating building codes into broader programmes

Sustainable building programmes in Mexico include the *Esta Es Tu Casa* (This Is Your House) programme started in 2007 by the National Housing Commission and the *Hipoteca Verde* (Green Mortgages) programme started in 2010 by the Mexican Worker's Housing Institute (INFONAVIT). Both programmes promote the introduction of technologies that increase the efficiency of home appliances. Both have been constantly extended over the course of their implementation. A more comprehensive approach was started in 2010, with the submission of the world´s first Nationally Appropriate Mitigation Action (NAMA) for the residential sector. This effort includes a NAMA for New Residential Buildings (NS-108), also called ECOCASA (Box 8.1), and a NAMA for Sustainable Housing Retrofit (NS-111). Both NAMAs support the design of houses following a high energy efficiency standard. The NS-108 has a total budget of USD 3 million for an implementation period of five years (2014-18) and an estimated emissions reduction of 1.2 $MtCO_2$. The NS-111 has a budget of USD 2 million and an emissions reduction target of 0.5 $MtCO_2$. These NAMAs provide good models of how federal governments can support cities to implement low-carbon policies in a particular sector. If scaled up, they also have the potential to change the entire buildings sector in Mexico through the acquisition of technical skills and the development of new technologies.

Table 8.4 Recommendations for space cooling and enforcement of building codes

Theme	Recommendation
Governance	Four-part governance of building energy codes and standards
	Roadmap for building energy codes and standards
	Cross-government policy relations and agreements
Capacity building	Public awareness programmes
	Awareness of energy efficiency for municipalities
	Certification of installers of air-conditioning equipment
	Implementation of pilot projects in municipalities
	Implementation of R&D programme for development of new technologies
	Data collection of buildings and systems characteristics
Policies and programmes	Removal of energy subsidies
	Third-party system for enforcement of building energy codes
	Incentives for compliant municipalities
	Public procurement
	Transition from NMXs to NOMs for whole building and building envelope
	Energy efficiency plans, audits and managers for buildings
	Benchmarking of building energy consumption
	Energy efficiency label for buildings
	Standards and energy labels for air-conditioning equipment
	Low-interest loans for energy-efficient buildings

Source: IEA (2015b).

Box 8.1 Case study: Federal policies for sustainable building promotion in cities: ECOCASA

The *Programa de Cooperación Financiera para la oferta de Vivienda Sustentable en Mexico* (Financial Co-operation Programme for Sustainable Housing in Mexico, ECOCASA) is a programme designed by the Mexican development bank *Sociedad Hipotecaria Federal* (SHF) in co-operation with the German development bank KfW and the Inter-American Development Bank (IADB). ECOCASA aims to change the buildings construction sector by fostering the construction of new buildings with a lower carbon footprint. For that, the programme provides financial incentives to housing developers in the form of loans with lower interest rates than market, under the condition of achieving a minimum reduction of 20% in CO_2 emissions in comparison with traditional construction methods, without increasing the final price to the buyer. For this comparison, a measurement, reporting and verification (MRV) system has been developed to measure the performance of every energy efficiency action and the overall performance. The NAMA has set three different levels of efficiency for the evaluation of the proposals based on international standards: Ecocasa 1, Ecocasa 2 and Passive House. Four different climate zones are also considered: hot and dry, hot and humid, moderate, semi-cold.

The programme was initiated in 2013 as part of Mexico's NAMA for new developments. During the first seven years of its implementation, the programme is helping to finance the development of 27 600 houses (benefiting about 108 000 people) and to finance an additional 1 700 green mortgages, saving 1 $MtCO_2$-eq emissions during their lifetime. Up to 2015, ECOCASA has provided loans of about USD 170 million to build 12 000 houses

(8 000 already built), and another 1 700 are in the process of being approved.

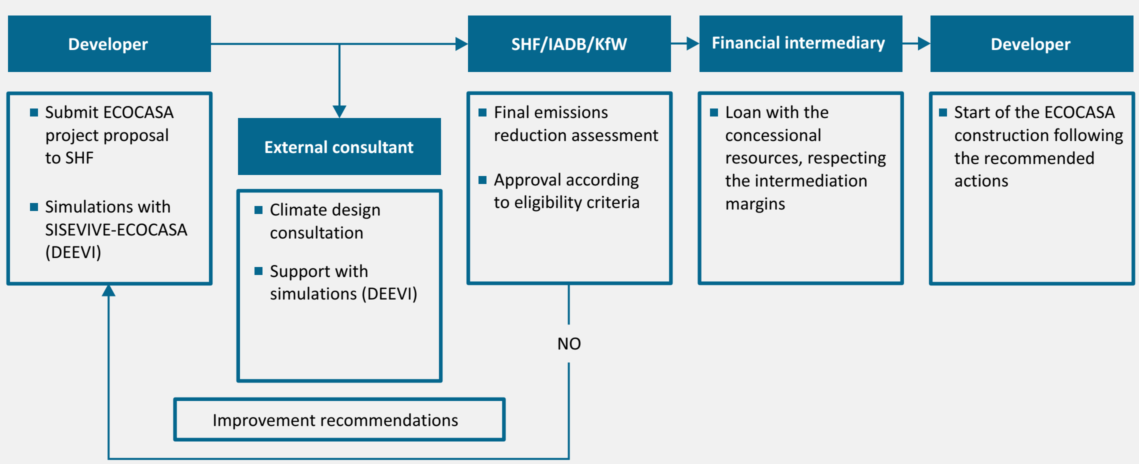
An innovation of the ECOCASA programme, compared with others previously implemented in Mexico, is the "whole house approach" in which the requirement for emissions reduction is set as a global objective for the entire house. "Such an approach has numerous benefits: It enables a simple and cost-efficient MRV system that captures the net efficiency improvements of a broad range of eco-technologies, building design, and building materials, it also enables stakeholders to find the most cost-efficient combination of these features and the tiered benchmark approach enables donors to target specific activities that align with their development priorities, and provides flexibility for regulators to increase the stringency of the programme over time" (UNFCCC, 2010).

To access the preferential interest rate that the ECOCASA programme offers, the housing developers need to pass a four-stage process designed by the inter-institutional team of SHF-KfW-IADB (Figure 8.6).

Houses developed under the ECOCASA programme also provide relevant benefits to their inhabitants in terms of comfort (temperatures of 20°C-25°C) and energy savings. Electricity and gas bills are predicted to be 28% or USD 200/year lower on average in an ECOCASA (Ashden, 2015). Those savings are particularly relevant when considering that ECOCASA is a programme for social housing.

The ECOCASA programme was recognised as a Lighthouse Activity by the UNFCCC during the United Nations Climate Change Conference in 2013 (COP19). In 2015, it also received the Ashden Award for Sustainable Buildings "not just for providing new homes that are sustainable as well as affordable, but [it] is also transforming the whole construction sector through its support to housing developers" (Ashden, 2015). The European Union has already added EUR 7 million from the LAIF Fund to foster the implementation of the Passive House standard, which can achieve a reduction of approximately 80% of the emissions in comparison with the baseline.

Figure 8.6 Four-stage process for ECOCASA programme



Source: SHF (2015), "Ecocasa Casas Eficientes para todos".

Key point *A simulation-based review process ensures efficiency and climate benefits of ECOCASA projects.*

Urban transportation

The rapid and relatively unplanned growth of Mexican cities has also led to challenges for transport in cities. Urbanisation proceeded mainly through low-density construction in regions surrounding cities where cheaper land was available after a constitutional reform that allowed the sale of former communal land surrounding the cities (*ejidos*). The immediate consequence of this "3D growth model" – distant, dispersed and disconnected (UN Habitat, 2011; IMCO/Centro Mario Molina/ctsEmbarq, 2013) – has been a dramatic increase in dependence on personal cars, which has resulted in direct economic, social and environmental consequences. The proliferation of low-density suburbs, together with the need for involvement of different municipalities to change legal, social and economic paradigms, has complicated funding and implementation of effective public transport systems. The lack of efficient and affordable public transport represents a logistic and financial burden to lower-salary workers, who face difficulties in accessing city centres. A comparison of city-centre residents and suburb dwellers shows that residents in the central areas of the Mexico Valley emit up to 35% less GHGs, dedicate four hours per week less to commuting and spend 15% less on transport costs (CMM, 2012). This comparison highlights the need for better urban planning and housing finance mechanisms that foster mixed-use and high-density developments. The need for enhanced focus on transport in cities was acknowledged in the National Development Plan 2013-2018, which was the first of its kind in Mexico in its inclusion of sustainable urban mobility as a key objective (PND, 2013).

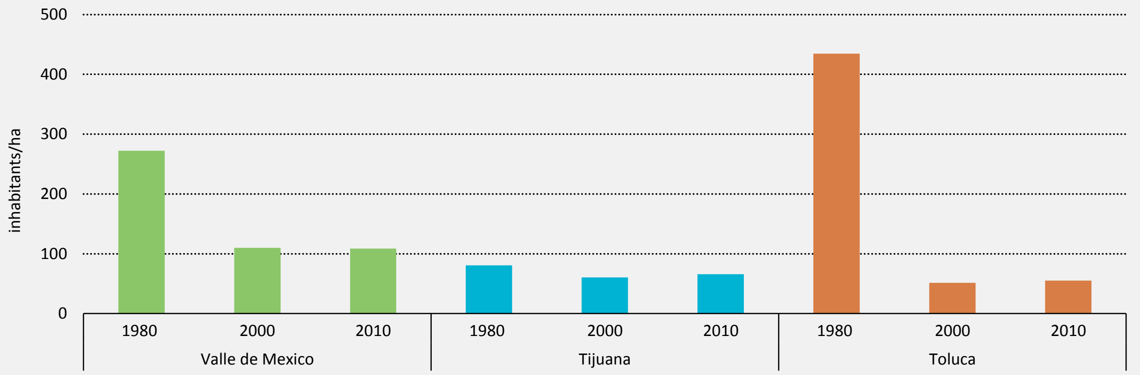
To achieve the 2DS targets, Mexican cities will need to transition to sustainable mobility patterns. This goal entails reducing trip distances as well as the total number of trips taken in personal vehicles. Measures to improve the fuel efficiency of both light- and heavy-duty vehicles will also be needed; regulations and fiscal (tax) measures on new vehicle registrations are two options for achieving this goal. Fuel switching (towards natural gas and biofuels) can also bring benefits to freight transport, especially for long-distance and mid- and heavy-duty trucks. Further electrification of freight transport could be rapidly implemented by modernising the intercity railway system. Actions should be taken immediately to accelerate the deployment of electric trains.

Mexico's most pressing challenge for implementing sustainable urban mobility is the current sprawling urban form. The so-called 3D growth model has informed years of rapid urbanisation based on low-density housing at the periphery of cities. The urban density of the largest metropolitan areas dropped rapidly between 1980 and 2000, with Toluca as the extreme case (Figure 8.7). Although the pace of sprawl has more recently decreased, and in some cases, the trends of declining population density have been reversed, Mexican cities are still far from the level of densification that would bring the benefits of economies of scale to their inhabitants.

The rapid sprawl of Mexico's cities has made urban residents car-dependent. Living far from jobs and daily activities, many Mexicans need to commute long distances by car every day. The low density and lack of integrated planning are substantial hurdles for the introduction of viable public transport. Together with the cross-border flow of used vehicles from the United States, and subsidies to fossil fuels (which have been phased out gradually since 2008), these development patterns have triggered rapid growth in ownership and use of private vehicles and consequently increasing congestion, air pollution and numbers of car accidents. From 2000 to 2010, the total number of automobiles in Mexico's 59 metropolitan areas almost doubled (INEGI, 2015). Meanwhile the amount of vehicle kilometres travelled tripled from 1990 to 2010 (ITDP Mexico, 2012).

The National Development Plan (PND, 2013) and the Climate Change Programme 2014-2018 (SEMARNAT, 2014) cite transport as a top priority for Mexico's sustainable development goals. The National Development Plan states the need to "improve urban mobility through mass urban transport systems coherent with sustainable development". It also expresses the need to accompany investments in public transport with measures favouring pedestrians, bikes and rational use of automobiles such as car-sharing and pooling (PND, 2013). To reach these goals, Mexico will need to transition towards more compact cities (see Chapter 5, Box 5.3), make cars less attractive and fully incorporate sustainable urban public and non-motorised transport into all major infrastructure-funding mechanisms.

Figure 8.7 Average urban density in Mexico



Source: IEA calculations, based on INEGI data.

Key point *In the 1980s and 1990s Mexico witnessed a phase of intense sprawl.*

Towards compact cities

For Mexico to realise its sustainable urban mobility goals, the country will need to change the urban form of its cities. This change must be combined with economic incentives and regulatory measures to reduce the use of private vehicles and with the provision of sufficient alternatives so that citizens can modify their behaviour patterns.

The most immediate and greatest challenge for Mexico's cities is to cease urban sprawl and foster the development of "compact cities". This challenge will require cities to reduce commute distances and improve the viability of more efficient modes of transport (including not only public transport but also walking and cycling). In this regard, the Ministry for Agrarian, Territorial and Urban Development (*Secretaría de Desarrollo Agrario, Territorial y Urbano* [SEDATU]) has introduced Urban Containment Perimeters and Certified Developments. These instruments are used to implement the strategy set by the National Urban Development Programme, which has the primary objective "to control the expansion of the urban frontier and consolidate cities to improve their inhabitants' quality of life" (PNDU, 2014). Toward this end, Urban Containment Perimeters restrict the growth of the cities by offering public incentives only to urban developments within a designated perimeter (Fundación IDEA, 2014). Certified Developments are areas of development designed to contribute to balanced growth and serve as a regional stimulus (SHF, DUIS, 2011). To this end they receive a subsidy from the federal government. They can be located inside an existing city to contribute to a re-densification strategy, or they can be independent, new developments. However, the National Urban Development Plan (PNDU) aims to use the Certified Developments as "a tool to control the urban expansion outside the Urban Containment Perimeters" (PNDU, 2014).

These two policy strategies are steps in the right direction: towards fostering intra-urban development as a means to re-densify already developed areas. Federal government support for projects that revitalise degraded or poorly developed areas inside cities can bring the appropriate incentives and capabilities to municipalities. In addition, metropolitan development plans can facilitate this process by integrating plans to consider the relationship between transport and the built environment, and to incentivise public-transport oriented development.[10]

Making car use less attractive while fostering public transport

Reducing transport emissions will also require increasing the costs of owning and operating personal cars. At the federal level, energy sector reform approved in 2013 will gradually liberalise the gasoline and diesel markets. This is the first crucial step in ensuring that the private costs of road transport align better with the social and environmental costs. Progress on this front is encouraging: while the energy reform set 2017 as the final year for fuel price subsidies, the Mexican Finance Ministry (*Secretaría de Hacienda y Crédito Público* [SHCP]) envisions collecting taxes on gasoline instead of paying a subsidy in 2016.

Some programmes are being proposed and implemented at the municipal level as well. A nationwide effort could help to raise the visibility of these efforts and facilitate knowledge transfer between cities. Local efforts could also be fostered by more active involvement of federal institutions such as SEDATU. Regulatory instruments to limit the use of private vehicles are also an important measure. Mexico City and the State of Mexico's driving restriction programme *Hoy No Circula* (No Driving Today) is one of the best-known and time-tested vehicle operating restriction programmes in the world. Initiated in 1989, it prohibits certain cars from operating on certain days, depending on their emissions performance (*Programa de Verificación Vehicular Obligatoria*).

Mexico has ample experience with the creation of trust funds for investment in urban public transport, with a prime example being the *Fondo Metropolitano* (Metropolitan Fund [MF]), created in 2006. Much of the funds, however, have been traditionally allocated to road infrastructure projects rather than public transport. The National Infrastructure Fund (*Fondo Nacional de Infraestructura* [FONADIN]) includes a specific programme for the support of public transport, the *Programa Federal de Apoyo al Transporte Urbano Masivo* (PROTRAM). The scope of PROTRAM includes "underground trains, metro, light rail, tram, bus rapid transit (BRT) and inter-modal integration projects". An important requirement for projects planned under the Urban and Transport Development Plan is that they serve to foster a more holistic approach to transport planning.

Since the first BRT was introduced in León in 2003, interest in BRT in other Mexican cities has grown rapidly. Presently 10 cities (Chihuahua, Ecatepec, Guadalajara, Guadalupe, Juárez, León, Mexico City, Monterrey, Nezahualcóyotl and Puebla) have built a total of 304 kilometres (km) across 15 corridors, and transport nearly 2 million passengers per day (Global BRT data, 2016). Mexico City's BRT system, Metrobus, stretches 105 km and carries 900 000 passengers per day across its five corridors (Box 8.2). As such, it is the largest and most widely used system in the country. Given their low costs relative to metro and light-rail systems and high throughput compared with conventional urban public buses, BRT systems could play an important role in the near future in the implementation of sustainable integrated land use and public transit strategies for Mexico's metropolitan areas. Nevertheless, as recognised in the PNDU, BRT systems not only require adequate funding but also need "integral federal support to guarantee appropriate institutional and managerial capability by the state and municipal governments to overcome all the commissioning challenges" (PNDU, 2014).

10 See also OECD recommendations for compact city policy strategies, which include the following: set explicit compact city goals; encourage dense and contiguous development at urban fringes; retrofit existing built-up areas; enhance diversity and quality of life in urban centres; and minimise adverse effects (OECD, 2012).

Box 8.2 BRT in Mexico City

BRT was introduced in Mexico City as part of a programme for improving air quality in the Valley of Mexico. The project received a grant of USD 5.8 million from the Global Environment Fund, supplemented by grants from the World Bank, the World Resources Institute, the Shell Foundation, bus manufacturers and fuel suppliers (Francke, Macías and Schmid, 2012; World Bank, 2009).

The first line of the BRT system, Metrobus, began operating in November 2005 (Table 8.5). During its first year, it transported 10 million passengers and reduced GHG emissions by an estimated 30 000 tonnes of CO_2-equivalent per year. Metrobus also led to a substantial reduction in exposure to local air pollutants; a study conducted by SEMARNAT reported a significant reduction in exposure to local criteria pollutants near Metrobus corridors: 23% for particulate matter (PM_{10}) and 50% for carbon monoxide (Vergara and Haeussling, 2007).

Key lessons learned

Inclusion: The local government of Mexico City was given the legal jurisdiction to expand the Metrobus system with or without the participation of the original operators. Line 1 was in many ways a platform and an experiment for demonstrating the benefits of BRT. An important success factor for Line 1 was the inclusion of transport workers as a way to support the social legitimacy of the project and allow scaling to other lines. After the success of Line 1, Mexico City made plans for the implementation of 12 more lines.

Learning from others: Peer-to-peer knowledge transfer with Curitiba, Brazil, and Bogotá, Colombia, was a key factor in accelerating the implementation of BRT in Mexico City. Operators were trained, and users were informed of the system benefits via public awareness campaigns. This flow of information also played a vital role in building trust among stakeholders.

Building trust: The implementation process faced two major challenges stemming from a lack of trust between the local government and operators. Once the operating company was established, operators were not comfortable with the fact that they would not be handling fare charges directly. Additionally, operators were sceptical about the economic benefits that Metrobus would bring to them in comparison with the previous public bus operating model.

Co-benefits: Metrobus was marketed as a package with multiple benefits for stakeholders. These benefits included reduced congestion and pollution; superior quality, integrated and faster service; reduced carbon emissions; better working and economic conditions for operators; and improved access to commercial activity. The benefits were clearly and convincingly articulated to all affected constituencies.

Flexibility and adaptability: The Metrobus case also demonstrates how the particular negotiating process for each line involved a very specific set of conditions. These conditions were a result of characteristics of economic activity in the area and of the interactions among operators. It also shows that financing models can (and should) adapt over time to reflect the economic situation of the city and the level of support provided by the federal government.

Table 8.5 Summary of BRT benefits in Mexico City

Line	Length (km)	Passengers per day	Emissions reduction per year (tCO_2-eq)	Accidents prevented per year	Time saved
1	30	480 000	50 000	30%	50%
2	20	180 000	30 000	17%	50%
3	17	140 000	20 000	n.a.	40%
4	28	65 000	10 000	n.a.	n.a.
5	10	55 000	12 000	n.a.	n.a.
6	20	145 000	20 000	n.a.	40%
7	17	100 000	17 000	40%	40%

Source: This case study was submitted by Rodrigo Villarroel Walker and Benoit Lefevre (World Resources Institute).

Other programmes being implemented in Mexico City that alter peoples' transport patterns include the parking management programme *Ecoparq* and the public bicycle rental system *Eco-bici*. Further efforts are needed to foster initiatives for car-pooling and car-sharing.

Public charging stations are an important initial step toward promoting EV deployment. Mexico City has already begun to install some charging stations. Nevertheless, much broader deployment will likely be needed, together with policies to facilitate the installation of such points at private parking spaces. Furthermore, incentives will be needed to reduce the price difference between EVs and conventional internal combustion engine vehicle technologies to encourage EV penetration in the passenger vehicle fleet. With a fairly well-developed domestic car-manufacturing industry, Mexico has the potential to reap benefits from the manufacture of EVs in its factories.

Supply and systems integration for cities

Non-hydro renewable energies are still a small component (4%) of Mexico's energy mix. Increasing private investment, together with appropriate policy instruments, can help to tap Mexico's vast renewable energy potential. The energy reform approved in 2013 has allowed private investment and aims to foster the development of renewable energy with the introduction of clean energy certificates. So far, the only renewable energy that has started to grow is wind power, mostly concentrated in the rural parts of the state of Oaxaca. In the future, growing cities and metropolitan areas could also rely on renewable energy supply. In this process, smart-grid technologies (such as smart meters and demand response systems) can be an important component for the urban sustainable energy transition. In addition, *ETP* results point to WTE and co-generation as important technology options for sustainable urban energy supply.

As far as **rooftop PV** is concerned, according to IEA estimates, the yearly per-capita potential ranges from in 949 kilowatt hours (kWh) (in Cancún, Quintana Roo), to 1 277 kWh (in Mexico City) and up to 2 119 kWh in Los Mochis, the most promising urban location in Mexico. Overall Mexican generation potential from rooftop PV could increase from 170.9 TWh to 205.5 TWh by 2050 – which would amount to a third of gross electricity generation in the 2DS. Tapping this potential has been difficult in the past under the conditions of a monopoly utility company that was not allowed to partner with private investors on power generation projects. Under the ongoing energy reform, private investment will become much easier, although the exact terms for individual sales to the grid have yet to be defined. Fiscal incentives for PV are in place already, including a 20% discount on property tax for residences generating more than 50% of their power needs. Companies using solar energy also receive a tax break on payrolls and water tariffs (Critchley, 2015). The important success factor going forward will be the establishment of clear rules and regulations. In addition, an independent and publicly available assessment of the PV potential could help mobilise homeowners to invest in their own power supply.

In terms of **WTE**, the Mexican National Climate Strategy (ENCC, 2013) identifies integral waste management, including the utilisation of biogas, as one of five mitigation actions. The generation of waste per inhabitant in Mexican cities stood at an average 360 kilogrammes (kg) per year (OECD, 2016). This level still leaves quite a bit of upside potential before reaching the OECD average of 522 kg/year. The WTE potential in Mexico is estimated at 31 petajoules (PJ) in 2015 in terms of primary energy, corresponding to a potential electricity generation of 8 TWh. This potential would increase to 245 PJ by

2050, due to growing population and higher collection rates, potentially covering 15% of residential power supply. Each municipality is responsible for its own waste management, according to Article 115 of the Mexican Constitution. However, according to Article 73, the federal congress has the ability to issue laws that help the federal, state and municipal governments to manage effectively all their environmental protection matters. This authority has led to the issuance of several federal standards, regulating the location, design, construction and operation of final waste disposition as well as the incineration of waste (IDB, 2013). To navigate the complex regulations and mobilise the needed investments and know-how, energy service companies could play an important role in starting to develop WTE in Mexico.

For decades, **co-generation** was a neglected area due to the closed nature of the power sector. The 2013 energy reform, which allows private entities to enter the power generation sector, has created significant opportunities for the technology. A large untapped co-generation potential – often located close to urban areas – now exists through the national oil company PEMEX. The company recently formed a co-generation and services division to ensure the utilisation of excess vapour and heat from the oil firm's industrial operations – especially at its refineries. PEMEX alone plans to add 5 GW of the 7 GW in co-generation projects that SENER foresees will be added to the country's generation capacity by 2020.

The enabling factor: Smart grids

Smart-grid technologies offer the ability to smooth peak demand and optimise supply-side management, demand-side management and storage – all of which support integration of renewables. For Mexico, smart-grid technologies can thus be considered primary enabling instruments for expanding renewable resources. These technologies can help Mexico meet clean energy targets by aiding in balancing the variability of solar and wind energy and can be deployed in urban areas to assist with accomplishing energy efficiency goals.

An example of the use of smart-grid technologies is their application in reducing the country's distribution grid losses. In 2011, the Mexican distribution network was experiencing more than 11% loss of all electricity generated due to technical losses (79%) and commercial losses or electricity theft (21%). These losses represented USD 2 446 million in revenue. The strategy to reduce losses (introduced in 2011 with actions until 2026) combines smart-grid technologies with a systematic evaluation mechanism to make improvements in both infrastructure and operational procedures. The long-term strategy estimates that targeted investments and planned actions can reduce losses by over 50%.

The development of smart grid technologies in Mexico is in its early stages, but is moving forward with efforts that include a pilot project in Polanco (Mexico City). Currently, three public entities are tasked with smart grid planning and implementation efforts: SENER, the electric utility (CFE), and the Energy Regulatory Commission (CRE). While CFE previously controlled all activities of the utility supply chain – including transmission, distribution and generation – the energy reform's deregulated market structure will open doors for new players in the development and management of different aspects of smart grids. The addition of more private participation in grid activities has also meant the institutionalisation of the National Control Centre as an independent system operator. The three government entities, as well as a variety of private participants, are now in a transition period and are in the process of adapting current roles and defining new roles, responsibilities and methods of co-operation together on national smart-grid strategies.

The unfolding regulatory framework must consider not only the deployment of smart grid technologies but also the Mexican renewable energy target of 35% of electricity generation from clean energy resources by 2024. This goal implies a significant increase in the use of renewable energy, particularly wind and solar. The National Energy Strategy recognises that smart grids could boost the integration of renewable energy into the grid, helping to meet national and international targets for renewables and GHG reduction. A stakeholder workshop organised jointly by the IEA and SENER in May 2015 elaborated a set of specific recommendations for the deployment of smart grids at the distribution system level in Mexico. First and foremost, it will be crucial to ensure co-ordination among key parties (e.g. policy makers, regulatory authorities, utilities, research institutions, academia and the private sector) to define the scope of smart grids and to enable streamlined implementation (IEA, 2015c).

Multilevel governance for Mexican cities

Implementing the energy transition involves the co-ordination of all levels of government in a complex field of technological, social and environmental issues. To date, this co-ordination is lacking in Mexico, with most of the policy and strategic initiative lying with the federal government, while much of the implementation is left by the constitution to municipalities. The result is a range of gaps in transforming the energy sector because of inadequate human resources and funding, information asymmetries or diverging objectives. Reforms in this area have started with the creation of SEDATU and plans for issuing a National Territorial Strategy. These reforms have been important steps forward for the co-ordination of the large number of institutions at the three levels of government that are involved in housing, transport and municipal services (OECD, 2015a).

The Mexican federal government has started to develop policies for the promotion of urban sustainability in three main areas: urban development, climate change and energy policies. Because municipalities and states aim to foster fundamental changes in cities, they must be involved to achieve policy coherence and successful implementation. Their inclusion requires a level of co-ordination difficult to reach among a large number of institutions with different objectives and agendas. The complexity increases when considering metropolitan areas that may include a large number of municipalities, can be spread across different states and may even have strong cross-border connections with US cities.

By design, the central government planning document is the National Development Plan (PND), which defines the objectives that are then supposed to inform state and municipal development plans. In practice, state-level plans include few explicit references back to the PND. But even when such references are to be found in policy documents, the follow-up cannot be taken for granted. Hence, appropriate co-ordination among the different levels of government becomes crucial for successful implementation of the different policies. Involvement of federal and state governments has the potential to facilitate co-ordination and provide the needed expertise and resources for cities to successfully implement sustainable urban energy systems.

Table 8.6 Overview of policy instruments at different levels of government

	Urban development	Climate change	Energy policy
Federal	PND National Housing Development Plan (PNV) PNDU National Infrastructures Development Plan INFONAVIT/FOVISSSTE/SHF SEDATU integrating urban and housing development competencies PROTRAM MF General Law on Human Settlements (*Ley General de Asentamientos Humanos*) 2014	General Law on Climate Change Special Climate Change Programme (*Programa Especial de Cambio Climático*, PECC) Reform of *Instituto Nacional de Ecología* into *Instituto Nacional de Ecología y Cambio Climático* (INECC) Creation of the National System for Climate Change and involvement of SEDATU	NOMs and NMXs Efficiency programmes supported by National Energy Efficiency Commission Programme for Sustainable Energy Use (*Programa para el aprovechamiento sustentable de la Energía* [PRONASE] 2014-18) Electricity Savings Fund - *Fideicomiso para el Ahorro de Energía Eléctrica* Law for Energy Transition (2015)
State	State development plans tend to refer to PND	Development of state level climate programmes with the support of INECC Members of the National System for Climate Change	
Municipal	Municipal development plans	Development of Municipal Climate Action Plans (PACMUN) with support from INECC and British Embassy Members of the National System for Climate Change	

Implementation of the federal government national plans (Table 8.6) requires strong co-ordination among institutions throughout the three levels of government. Indeed the Mexican constitution explicitly calls for this, albeit only when cities form a "demographic continuity" across federal state borders (Article 115). In addition, Article 122 of the Mexican Constitution provides for Metropolitan Commissions to enable co-ordination among municipalities as well as between the latter and the federal states. Furthermore, the General Law of Human Settlements enables the federal administration and states to agree on regional planning mechanisms to co-ordinate actions and investments, with the participation of the respective municipalities (Article 12).

The challenge for federal policy makers in this sense is twofold: i) to create the mechanism by which the federal government can channel technical, managerial and economic resources; and ii) to foster effective co-ordination among federal ministries, states, municipalities and local stakeholders (mainly but not only governments). The Mexican MF and CAMe show how these objectives can be achieved and are promising mechanisms that could be further strengthened and scaled up.

Box 8.3 FMVM – Example of federal government involvement

Decision-making process

The Mexican federal government is heavily involved in the decision making of the FMVM, which is part of a federal budgetary policy instrument called Economic Provisions and Wages, or Ramo 23. SEDATU is in charge of deciding which urban areas are declared metropolitan centres, with the approval of CONAPO and INEGI. The metropolitan area designation allows states and municipalities to access the funds made available by FMVM. Project proposals and the requests for funds are typically submitted by the states making up the metropolitan area. The responsibility for approving fund requests and determining the amount to be assigned falls on three entities: the Council for Metropolitan Development of the Chamber of Deputies, with support of the technical committee of the trust that administers the funds, and a technical sub-committee that evaluates prospective projects. However, SHCP issues the operative rules that guide the prioritising and project selection process. Funds are administered by a trust that releases funds directly to the entity that executes the project. Funded projects must be aligned with the recent versions of the PND 2013-2018, the National Plan of Infrastructure 2014-2018, the National Plan for Urban Development 2014-2018, and regional and municipal plans of urban development.

Key projects

The FMVM has historically attracted more funds than other metropolitan areas, but progressively decreasing from 64% in 2008 to 39% in 2015. This decline has been in part because the number of metropolitan areas included in the FMVM has increased from 7 in 2008 to 47 in 2015. In the period 2006-2009, the funds assigned to FMVM were mostly for three purposes: roads (~50%), water supply (~25%) and public transportation (~15%) (CIDE, 2014). The importance given to roads and car-oriented projects continued in 2014: with MXN 3 937 million assigned, 46% of the funds were dedicated to road paving, building new infrastructure and smarter stop lights. Solid waste management increased to 22% and public lighting to 8%, while water and sanitation decreased to 7% and public transportation to 4%.

The way funds are assigned is also a signal of the approach that each sub-region of the Valley of Mexico is taking to solve its problems (Table 8.7). In the State of Mexico, 64% of the funds were assigned to car-oriented projects, followed by 14% assigned to water-related projects and 13% assigned to safety, housing and social projects. The distribution of funds in the State of Hidalgo is similar to that of the State of Mexico. However, the picture is very different for Mexico City, where 47% of the funds were assigned to solid waste management projects, followed by 25% for car-oriented development and 16% for public lighting.

Table 8.7 Distribution of funds in three Mexican states

	State of Mexico	Mexico City	Hidalgo
Car-oriented transportation	64%	25%	69%
Public transportation	7%	0%	8%
Alternative mobility	1%	5%	0%
Public and green spaces	1%	8%	4%
Solid waste management	0%	47%	0%
Social projects, housing and safety	13%	0%	13%
Water supply and sanitation	14%	0%	7%
Public lighting	0%	16%	0%

Source: This case study was submitted by Rodrigo Villaroel Walker and Benoit Lefevre (World Resources Institute).

Instruments for bridging multiple levels of governance: The Mexican Metropolitan Fund (MF)

The MF, created in 1998, is a policy instrument created to improve the economic competitiveness, sustainability and productivity of metropolitan areas. Special attention is dedicated to plans, evaluations and projects that address roads and vulnerability to natural, environmental and demographic phenomena. Originally created as an instrument for the bilateral co-ordination of the State of Mexico and the federal district, the MF became active in 2006 with its incorporation into the federal budget and the creation of a trust fund with an initial endowment of MXN 1 billion (EUR 56 million). In 2014, the fund reached MXN 9.9 billion (EUR 552 million) and has been expanded to include 47 metropolitan areas (CIDE, 2014). The MF represents an opportunity for Mexico to engage cities across the country in the development of comprehensive metropolitan policies. This way, the MF has the potential to establish a new paradigm for the development and implementation of urban policies across Mexico. The operational rules of the MF establish the requirement for projects to be coherent with the PND. Sustainability is expressed as the fund's first objective.

Fondo Metropolitano of the Valley of Mexico (FMVM) serves as a vehicle for channelling federal funds to projects that are aligned with recent versions of national development plans and is an opportunity to address issues that concern the metropolitan areas as a whole (Box 8.3). However, no urban development plans yet exist at the metropolitan level. The pattern shown by the assignment of funds in 2014 suggests that projects are mostly focused on solving problems specific to each of the sub-regions of the Valley of Mexico. FMVM appears to be used not as a co-ordinating instrument among sub-regions but instead as a way for the federal government to support local initiatives that cannot necessarily be labelled as metropolitan.

The involvement of various federal and state government institutions and agencies contributes to transparency throughout the decision-making process. Despite the complex chain of decision making, no evidence exists that this complexity has created administrative barriers for FMVM. However, decisions are made mostly at the federal and state level without the participation of municipalities and delegations. Funded projects are, therefore, concerned with state-level priorities such as main transport arteries and main sewer drainage pipelines.

Although FMVM has a set of operative rules, the rules lack a focused definition of the agency's objectives, making it difficult to prioritise projects on the basis of their impact broadly on sustainability. Projects are justified mostly on a financial basis. The vast majority of the projects approved in 2014 were related to paving roads and avenues and building new infrastructure (e.g. bridges and distributors), which tends to attract more cars and congestion in the long run. The main thrust of FMVM was not public transport and alternative mobility. Projects involving bicycle programmes, improvement of pedestrian bridges and public transport amounted to only 7%.

Instruments for bridging multiple levels of governance: The Environmental Commission CAMe

CAMe is a metropolitan commission based on Article 122 of the Mexican Constitution. It has shown positive results in solving certain environmental and pollution issues through policy co-ordination among all the levels of government at the metropolitan level (Box 8.4). Established by the Mexican federal government in 2013 as an extension of the previous Metropolitan Environmental Committee to include all the municipalities included in the so-called megalopolis,[11] it has been developing and monitoring the *Programa para Mejorar la*

11 The megalopolis combines all municipalities that belong to the metropolitan zones of the capitals of the states bordering the Valley of Mexico, plus municipalities that have a close functional relationship with Mexico City – a total of 189 municipalities, including the 16 "delegaciones" of the federal district.

Calidad del Aire en la Zona Metropolitana del Valle de México – a programme for the control of the air quality in Mexico City (PROAIRE). The PROAIRE programme was initially launched in 1990; since then, other programmes such as Metrobus (Box 8.2), *Eco-bici* and *Hoy No Circula* have been initiated.

Box 8.4 CAMe: Example of metropolitan policy co-ordination

Decision-making process

The governing body of CAMe is constituted by a federal entity, SEMARNAT, and the governors of the federal district (Mexico City) and five states (México, Hidalgo, Puebla, Tlaxcala and Morelos). The six governors have the voting right to decide the policies that will be implemented individually by each state. The commission itself has no executive functions and can only provide technical recommendations. The main purpose is to co-ordinate actions for addressing air pollution across the Valley of Mexico, and it is expected to expand to biodiversity, sanitation, solid waste management and forest fires. An executive co-ordinator operates within CAMe, supported by a scientific committee, to recommend lines of actions to the governing bodies. Through its scientific committee, CAMe also provides knowledge products and capacity-building programmes. A sub-committee evaluates and monitors projects.

CAMe is partially funded by a trust fund, *Fideicomiso Ambiental del Valle de México* (Environmental Trust for the Valley of Mexico), established by the federal government in 1992 to fund projects that address environmental pollution, and partially by contributions from the various states. Contributions to this fund come directly from a portion of the fees charged to vehicle owners during their verification of exhaust emission tests.

Key projects

So far, the main activity of CAMe is related to two programmes: Hoy No Circula and vehicle verification of exhaust emissions, both under PROAIRE. Hoy No Circula restricts the circulation of cars on certain days of the week. The number of days that a car is not allowed to circulate depends largely on car performance during the verification of exhaust emissions. Vehicle owners are required to carry out these tests every six months.

Source: This case study was submitted by Rodrigo Villaroel Walker and Benoit Lefevre (World Resources Institute).

CAMe represents an example of regional co-ordination of policies with the financial support of the federal government. Although SEMARNAT can provide advice regarding alignment with federal plans to the governing body of CAMe, the decision making falls on the governors. In contrast with MF, CAMe was, therefore, not conceived as an instrument to implement federal policies and plans. However, CAMe does have the capability of formulating co-ordinated policies that consider the metropolitan phenomenon.

The Mexican law gives a large degree of autonomy to states, so in principle the CAMe model could be replicated in other states that share metropolitan areas. A potential barrier for replicating CAMe is the lack of funding. Other metropolitan areas might not have the economy of scale that the Valley of Mexico metropolitan region has, which makes the collection of fees from vehicle verification a viable funding source, and more federal resources might be required. Limited funding is also the reason for the challenges that CAMe faces in expanding its competency to other issues beyond air pollution.

Outlook

A constitutional reform initiative to specify the obligation for municipalities to incorporate aspects of their respective metropolitan zones into their development plans has not yet been taken up. However, at the federal level, the Chamber of Deputies and the Senate have created special commissions dedicated to metropolitan development. The PND, as well as the PNV and the PNDU, also stress the objective of co-ordination among the various levels of government. The political will to upgrade metropolitan considerations and work towards more integrated planning is there. Now similarly decisive implementation has to follow.

Recommended actions for the near term

In 2012, Mexico became the first Latin American country to pass a law with specific targets for GHG emissions reduction, including an ambitious objective to halve CO_2 emissions by 2050. The *ETP* 2DS shows that this goal could be achieved, including an almost complete decarbonisation of the power sector. In the Mexican 2DS, more than half of the national CO_2 emission reduction potential is achieved in urban buildings and urban transportation systems.

In the buildings sector, more ambitious policies and economic incentives are needed to change the current patterns. Increasing urbanisation and wealth are changing the patterns of energy consumption of households as well as housing construction methods. Space cooling demand will rapidly grow in the near future. Policies should be put in place to reduce the energy used to provide cooling and, more importantly, to reduce the need for cooling in the first place. This is all the more important in view of two emerging trends: firstly, new appliances are being more generally introduced. And secondly, houses are being designed in ways that abandon traditional Mexican methods for keeping houses cool, including using building orientation, the use of natural and constructed shading, and cool colours on building surfaces and roofs. In view of these trends, existing building codes will have to be enforced to avoid the challenges that new non-traditional housing developments will bring. Their effective enforcement and monitoring will require actions in terms of governance, capacity building, and new policies and programmes. These actions should combine the need for creating long-term visions and action plans, involvement of municipalities and citizens, economic incentives, and regulatory mandates. A progressive elimination of electricity subsidies could help to incentivise energy efficiency measures in the residential sector.

Past urban sprawl has led to inefficient transport patterns with negative consequences for the environment, as well as negative economic and social impacts. Mexican cities and metropolitan areas have been growing without proper densification. Changing the urban form of Mexico's cities and metropolitan areas is needed to unlock them from a car-oriented development. The current PND and PNDU point in the right direction by promoting policies for compact cities. The integration at the federal level of the urban and housing development responsibilities under the new SEDATU is another step in the right direction.

The development of large public transport systems is also critical. Investment in BRT corridors will need to be accompanied by the development of the appropriate feeder systems. Investments also need to move from car-oriented projects to urban mobility initiatives. An increase in vehicle fuel efficiency would be beneficial. To achieve that, the fuel economy standards need to be implemented and monitored, including the standard approved in 2013 for light-duty vehicles. All measures aimed at reducing the use of private vehicles should also offer appropriate alternatives to be able to change transportation behaviours. Measures to accelerate the introduction of EVs can help meet 2DS deployment targets in the mid-2020s. In fact, the deployment of charging points in Mexico City and some economic incentives are currently being implemented, but they are not yet sufficient to achieve the 2DS.

Regarding energy supply, Mexico's vast renewable energy potential is still largely untapped. The share of renewables in gross electricity generation increases to more than half by 2050 in the 2DS, including deployment of concentrated solar power, solar PV and onshore wind. Such a deployment of renewables will require a much smarter grid, and cities with their high density are the prime location for certain renewable energy technologies, such as rooftop solar energy. The involvement of all three levels of government is needed to achieve the transition towards sustainable urban energy systems. Co-ordination among many municipalities and states that may have different political objectives can be challenging. To address the legacy of sprawl and ensure sustainable urban development for the future, integrated land-use planning will be enabled only if existing mechanisms for policy co-ordination and implementation are further enhanced. Programmes such as ECOCASA, ad-hoc institutions such as CAMe and dedicated trust funds such as MF have accumulated experience with such co-ordination and should be scaled up and turned into active promoters of compact cities.

Overall, Mexico has shown a lot of political will to lead on international climate action and has also taken initial steps towards greater urban energy sustainability by addressing key issues in national plans and strategies. However, the challenge of implementation at the local level remains and needs to be tackled much more forcefully to cope with the coming urban challenges the country faces and to ensure its cities' potential is actually tapped.

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Annexes

Analytical Approach

Energy Technology Perspectives 2016 (ETP 2016) applies a combination of back casting and forecasting over three scenarios from now to 2050. Back casting lays out plausible pathways to a desired end state. It makes it easier to identify milestones that need to be reached, or trends that need to change promptly, in order for the end goal to be achieved. The advantage of forecasting, where the end state is a result of the analysis, is that it allows greater considerations of short-term constraints.

The analysis and modelling aim to identify the most economical way for society to reach the desired outcome, but for a variety of reasons the scenario results do not necessarily reflect the least-cost ideal. Many subtleties cannot be captured in a cost optimisation framework: political preferences, feasible ramp-up rates, capital constraints and public acceptance. For the end-use sectors (buildings, transport and industry), doing a pure least-cost analysis is difficult and not always suitable. Long-term projections inevitably contain significant uncertainties, and many of the assumptions underlying the analysis will likely turn out to be inaccurate. Another important caveat to the analysis is that it does not account for secondary effects resulting from climate change, such as adaptation costs. By combining differing modelling approaches that reflect the realities of the given sectors, together with extensive expert consultation, *ETP* obtains robust results and in-depth insights.

Achieving the *ETP 2016* 2°C Scenario (2DS) does not depend on the appearance of breakthrough technologies. All technology options introduced in *ETP 2016* are already commercially available or at a stage of development that makes commercial-scale deployment possible within the scenario period. Costs for many of these technologies are expected to fall over time, making a low-carbon future economically feasible.

The *ETP* analysis takes into account those policies that have already been implemented or decided. In the short term, this means that deployment pathways may differ from what would be most cost-effective. In the longer term, the analysis emphasises a normative approach, and fewer constraints governed by current political objectives apply in the modelling. The objective of this methodology is to provide a model for a cost-effective transition to a sustainable energy system.

To make the results more robust, the analysis pursues a portfolio of technologies within a framework of cost minimisation. This offers a hedge against the real risks associated with the pathways: if one technology or fuel fails to fulfil its expected potential, it can more easily be compensated by another if its share in the overall energy mix is low. The tendency of the energy system to comprise a portfolio of technologies becomes more pronounced as carbon emissions are reduced, since the technology options for emissions reductions and their potentials typically depend on the local conditions in a country. At the same time, uncertainties may become larger, depending on the technologies' maturity levels and the risks of not reaching expected technological development targets.

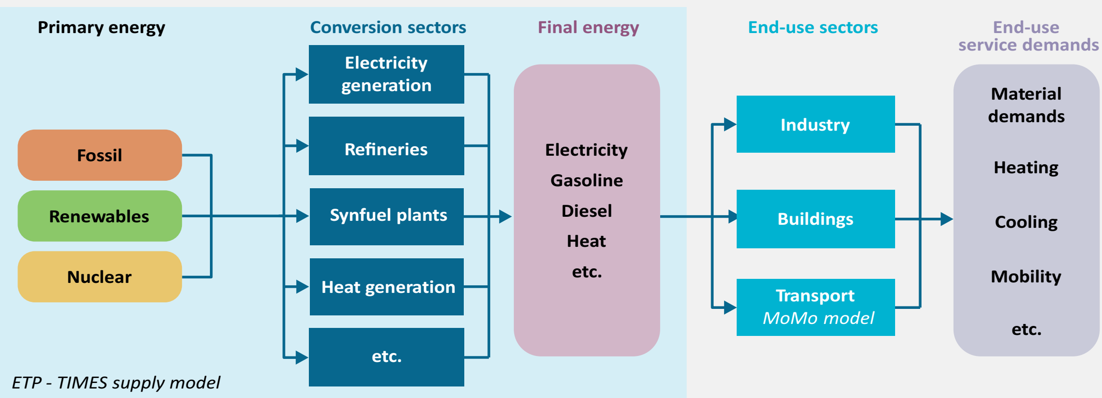
ETP model combines analysis of energy supply and demand

The ETP model, which is the primary analytical tool used in *ETP 2016*, supports integration and manipulation of data from four soft-linked models:

- energy conversion
- industry
- transport
- buildings (residential and commercial/services).

It is possible to explore outcomes that reflect variables in energy supply (using the energy conversion model) and in the three sectors that have the largest demand, and hence the largest emissions (using models for industry, transport and buildings). The following schematic illustrates the interplay of these elements in the processes by which primary energy is converted to the final energy that is useful to these demand-side sectors (Figure A.1).

Figure A.1 Structure of the ETP model



Notes: TIMES = The Integrated MARKAL-EFOM System, MoMo = Mobility Model.

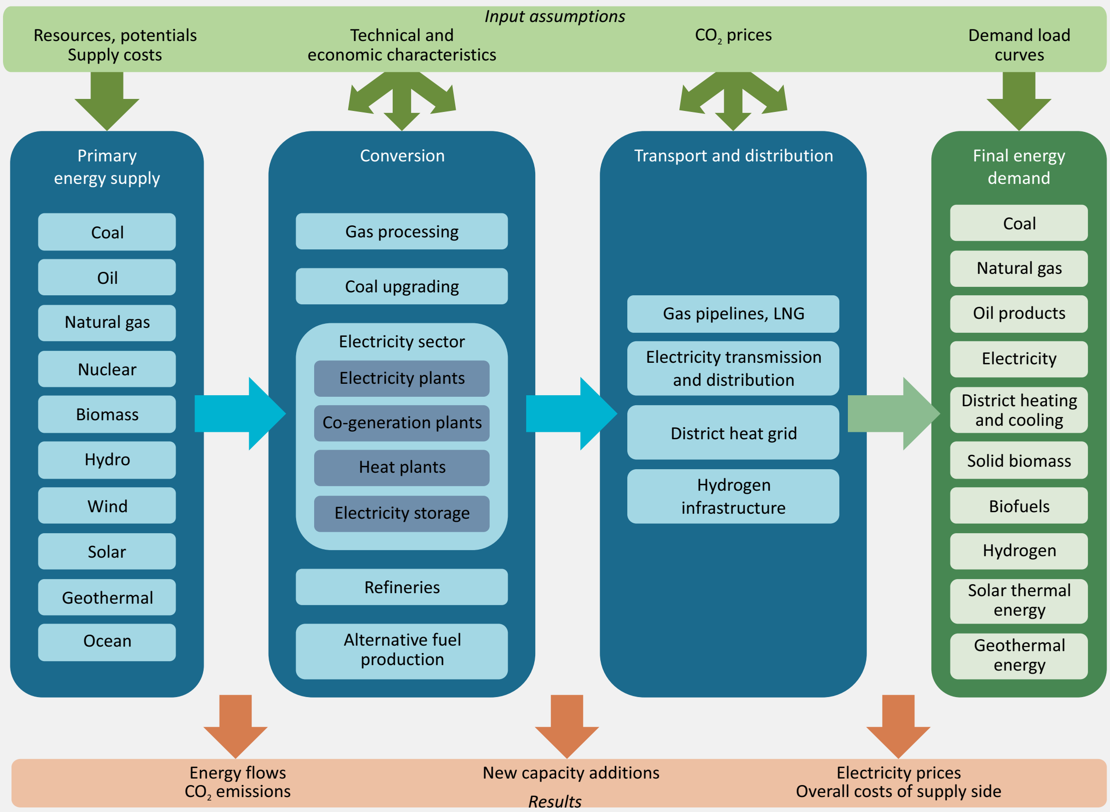
Key point *The ETP model enables a technology-rich, bottom-up analysis of the global energy system.*

ETP-TIMES model for the energy conversion sector

The global ETP-TIMES model is a bottom-up, technology-rich model that covers 28 regions and depicts a technologically detailed supply side of the energy system. It models from primary energy supply and conversion to final energy demand up to 2075. The model is based on the TIMES (The Integrated MARKAL EFOM System) model generator, which was developed by the Energy Technology Systems Analysis Programme (ETSAP) Implementing Agreement of the International Energy Agency (IEA) and allows an economic representation of local, national and multi-regional energy systems on a technology-rich basis (Loulou et al., 2005).

Starting from the current situation in the conversion sectors (e.g. existing capacity stock, operating costs and conversion efficiencies), the model integrates the technical and economic characteristics of existing technologies that can be added to the energy system. The model can then determine the least-cost technology mix needed to meet the final energy demand calculated in the ETP end-use sector models for industry, transport and buildings (Figure A.2).

Figure A.2 Structure of the ETP-TIMES model for the conversion sector



Notes: CO_2 = carbon dioxide; LNG = liquefied natural gas; co-generation refers to the combined production of heat and power.

Key point *ETP-TIMES determines the least-cost strategy in terms of supply-side technologies and fuels to cover the final energy demand vector from the end-use sector models.*

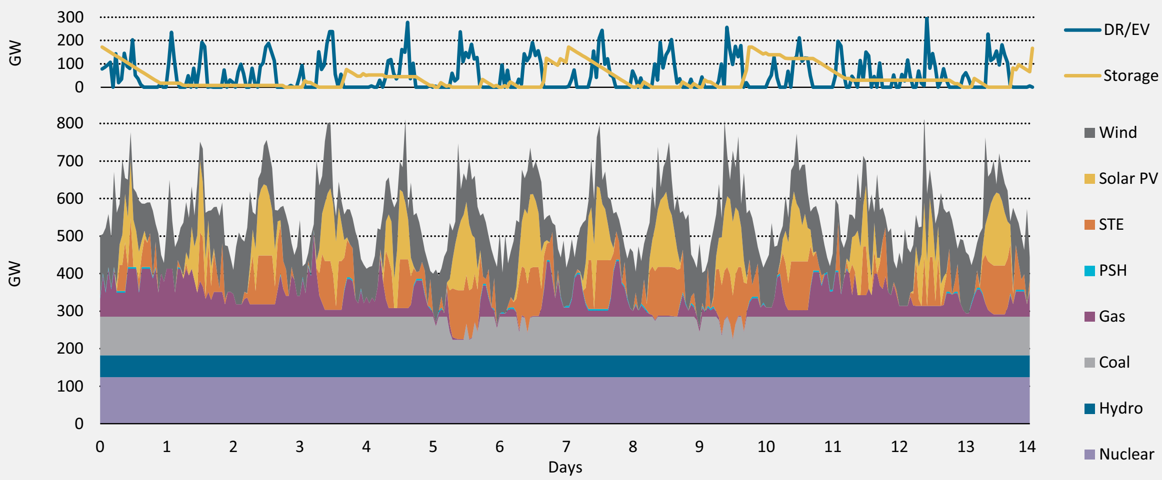
Technologies are described by their technical and economic parameters, such as conversion efficiencies or specific investment costs. Learning curves are used for new technologies to link future cost developments with cumulative capacity deployment.

The ETP-TIMES model also takes into account additional constraints in the energy system (such as fossil fuel resource constraints or emissions reduction goals) and provides detailed information on future energy flows and their related emissions impacts, required technology additions and the overall cost of the supply-side sector.

To capture the impact of variations in electricity and heat demand, as well as in the generation from some renewable technologies on investment decisions, a year is divided into four seasons, with each season being represented by a typical day, which again is divided into eight daily load segments of three hours' duration.

For a more detailed analysis of the operational aspects in the electricity sector, the long-term ETP-TIMES model has been supplemented with a linear dispatch model. This model uses the outputs of the ETP-TIMES model for the 2050 electricity capacity mix for a specific model region and analyses an entire year with one-hour time resolution using datasets for wind production, solar photovoltaic production, and hourly electricity demand for a year. Given the hourly demand curve and a set of technology-specific operational constraints, the model determines the optimal hourly generation profile, as illustrated in Figure A.3 for the 2DS in 2050 over a two-week period. To increase the flexibility of the electricity system, the linear dispatch model can invest in electricity storage or additional flexible generation technologies (gas turbines). Demand response by modifying the charging profile of electric vehicles (EV) is a further option depicted in the model in order to provide flexibility to the electricity system.

Figure A.3 **Dispatch in the United States over a two-week period in 2050 in the 2DS**



Notes: DR/EV = demand response/electric vehicles; PV = photovoltaics; STE = solar thermal electricity; PSH = pumped storage hydro.

Key point *The linear dispatch model analyses the role of electricity storage, flexible generation and demand response*

This linear dispatch model represents storage in terms of three steps: charge, store, discharge. The major operational constraints included in the model are capacity states, minimum generation levels and time, ramp-up and -down, minimum downtime hours, annualised plant availability, cost considerations associated with start-up and partial-load efficiency penalties, and maximum storage reservoir capacity in terms of energy (megawatt hours [MWh]).

Model limitations include challenges due to a lack of comprehensive data with respect to storage volume (MWh) for some countries and regions. Electricity networks are not explicitly modelled, which precludes the study of the impacts of spatially dependent factors such as the aggregation of variable renewable outputs with better interconnection. Further, it is assumed that future demand curves will have the same shape as current curves. A bottom-up approach starting from individual energy service demand curves by end-use technology would be useful in refining this assumption, but is a very data-intensive undertaking that faces the challenge of a lack of comprehensive data.

Industry sector model

Industry is modelled using TIMES-based linear optimisation models for three energy-intensive sectors (iron and steel, cement and aluminium), and technology-rich stock accounting simulation models[1] that cover the remaining two energy-intensive sectors (chemicals and petrochemicals, and pulp and paper). The five sub-models characterise the energy performance of process technologies from each of the energy-intensive sub-sectors, including 39 countries and regions. Typically, raw materials production is not included within the boundaries of the model, with the exception of the iron and steel sector, in which energy use for coke ovens and blast furnaces is covered. Due to the complexity of the chemicals and petrochemicals sector, the model focuses on five products that represent about 47% of the energy use of the sector: ethylene, propylene, BTX[2], ammonia and methanol.

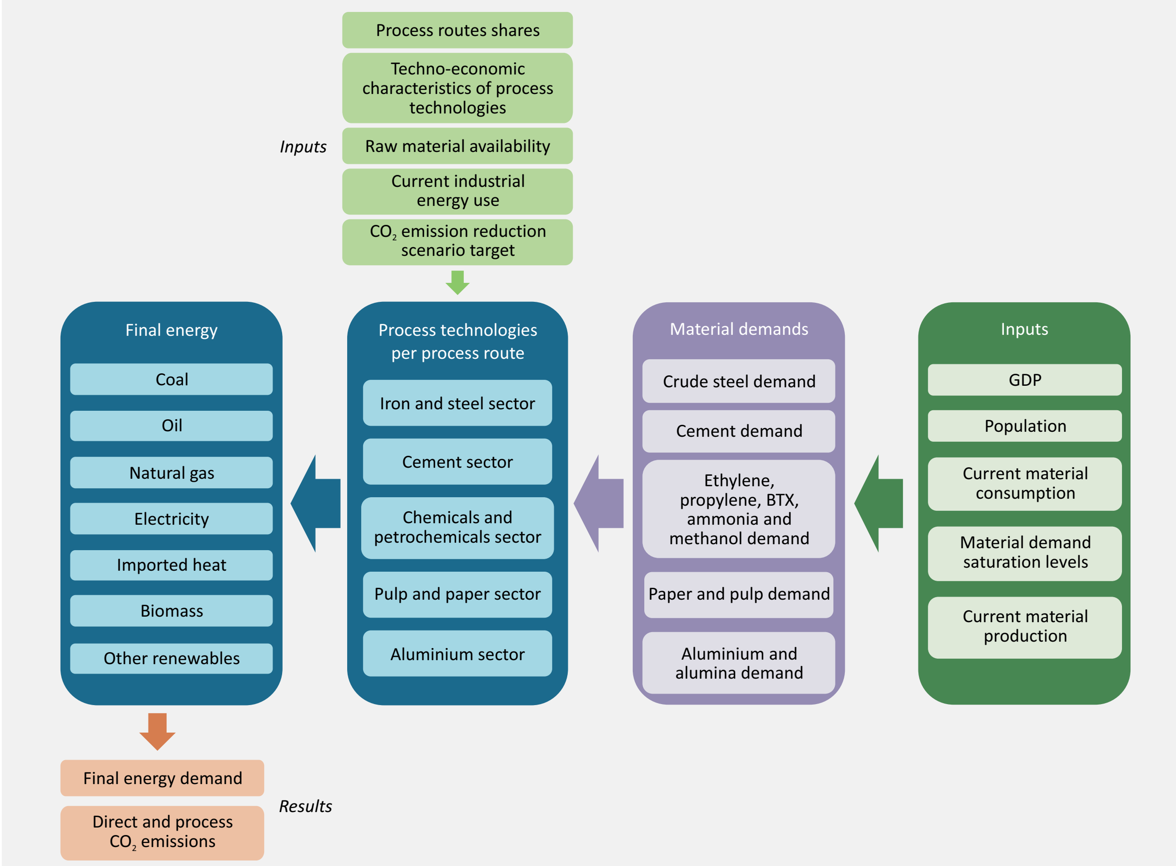
Demand for materials is estimated based on country- or regional-level data for gross domestic product (GDP), disposable income, short-term industry capacity, current materials consumption, regional demand saturation levels derived from historical demand intensity curves, and resource endowments (Figure A.4). Total production is simulated by factors such as process, age structure (vintage) of plants and stock turnover rates. Overall production levels are similar across scenarios, but means of production differ considerably. For example, the same level of crude steel production is expected in both the 6°C Scenario (6DS) and the 2DS, but the 2DS reflects a much higher use of scrap (which is less energy-intensive than production from conventional raw materials).

Each industry sub-model is designed to account for sector-specific production routes for which relevant process technologies are modelled. Industrial energy use and technology portfolios for each country or region are characterised in the base year based on relevant energy use and material production statistics for each energy-intensive industrial sub-sector. Changes in the technology and fuel mix as well as efficiency improvements are driven by exogenous assumptions on penetration and energy performance of best available technologies (BATs), constraints on the availability of raw materials, techno-economic characteristics of the available technologies and process routes, and assumed progress on demonstrating innovative technologies at commercial scale. Thus, the results are sensitive to assumptions on how quickly physical capital is turned over, relative costs of the various options, and incentives for the use of BATs for new capacity.

The industry model allows analysis of different technology and fuel switching pathways in the sector to meet projected material demands within a given related CO_2 emissions envelope in the modelling horizon.

1 The ETP Industry model is currently in a transition phase as it is being migrated to the TIMES modelling platform.
2 BTX includes benzene, toluene and xylene.

Figure A.4 Structure of the ETP-Industry model



Key point *Based on socio-economic assumptions and statistical information, the industry model projects material demands, which are then used to determine the final energy consumption and direct CO_2 emissions of the sector, depending on the energy performance of process technologies and technology choice within each of the available production routes.*

Modelling of the transport sector in the Mobility Model (MoMo)

Overview

The mobility model (MoMo) is a technical-economic database spreadsheet and simulation model that enables detailed projections of transport activity, vehicle activity, energy demand, and well-to-wheel GHG and pollutant emissions according to user-defined policy scenarios to 2050.

MoMo comprises:

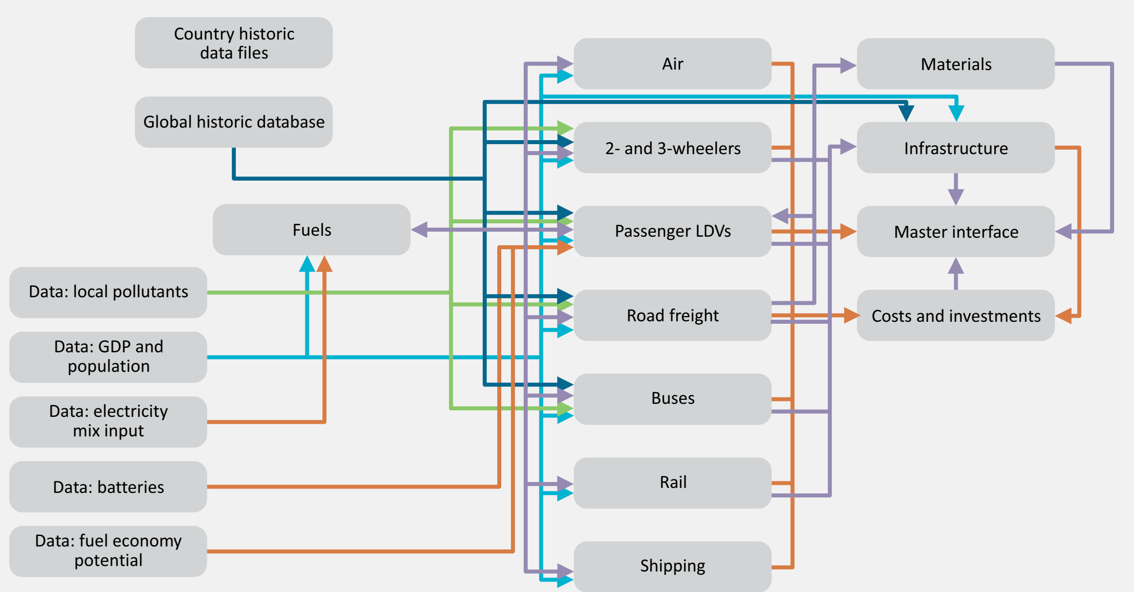
- 27 countries and regions, which are aggregated into 4 OECD regional clusters and 11 groups of non-OECD economies
- historic data from 1975 to 2013 (or 1990 to 2013 for certain countries)
- simulation model in five-year time steps, for building scenarios to 2050 based on "what if" analysis and backcasting
- disaggregated urban versus non-urban vehicle stock, activity, energy use and emissions (for methodological details, see Annex F at www.iea.org/etp/etp2016/annexes)

- all major motorised transport modes (road, rail, shipping and air), providing passenger and freight services
- a wide range of powertrain technologies (internal combustion engines, including gasoline, diesel, and compressed and liquefied natural gas, as well as hybrid electric and electric vehicles [including plug-in hybrid electrics – PHEVs, and battery-electric vehicles – BEVs], and fuel-cell electric vehicles [FCEV])
- associated fuel supply options (petroleum gasoline and diesel, biofuels [ethanol and biodiesel via various production pathways] and synthetic fuel alternatives to liquid fuels [coal-to-liquid – CTL and gas-to-liquid – GTL], gaseous fuels including natural gas [compressed natural gas – CNG and liquefied petroleum gas – LPG] and hydrogen via various production pathways, and electricity [with emissions according to the average national generation mix as modelled by the ETP TIMES model in the relevant scenario]).

MoMo further enables estimation of scenario-based costs of vehicles, fuels and transport infrastructure, as well as the primary material inputs required for the construction of vehicles, related energy needs and resultant GHG emissions.

To ease the manipulation and implementation of the modelling process, *MoMo* is split into modules that can be updated and elaborated upon independently. Figure A.5 shows how the modules interact with one another. By integrating assumptions on technology availability and cost in the future, the model reveals, for example, how costs could drop if technologies were deployed at a commercial scale and allows fairly detailed bottom-up "what-if" modelling, especially for passenger light-duty vehicles and trucks (Fulton et al. 2009).

Figure A.5 MoMo structure



Note: LDV = light-duty vehicle.

Key point *MoMo covers all transport modes and includes modules on local air pollutants and on the costs of fuels, vehicles and infrastructure as well as analysis on the material needs for new vehicles.*

Data sources

The *MoMo* modelling framework relies upon compiling and combining detailed data from various sources on vehicles in each of the countries/regions to estimate aggregate energy consumption, emissions and other energy-relevant metrics at the country/regional level.

Historic data series have been collected by MoMo modellers from a wide variety of public and proprietary data sources for more than a decade. National data are gathered primarily from the following organisations: (1) national and international public institutions (e.g. the World Bank, the Asian Development Bank and Eurostat); (2) national government ministries (e.g. departments of energy and transport, and statistical bureaus); (3) federations, associations, and non-governmental organisations (e.g. JAMA, KAMA and Naamsa); (4) public research institutions (e.g. peer-reviewed papers and reports from universities and national laboratories); (5) private research institutions (e.g. ICCT); and (6) private business and consultancies (e.g. POLK, Segment Y, and other major automotive market research and analysis organisations, in addition to major energy companies and automobile manufacturers themselves). Full details on data sources on a national or regional basis are documented in the regional data files of MoMo.

Calibration of historical data with energy balances

The framework of estimating average and aggregate energy consumption for a given vehicle class *i* can be neatly summarised by the ASIF identity (Schipper, 2000):

$$F = \sum_i F_i = A \sum_i \left(\frac{A_i}{A}\right)\left(\frac{F_i}{A_i}\right) = A \sum_i S_i I_i = F$$

where: F = total fuel use [MJ/year]; A = vehicle activity [vkm/year]; I = energy intensity [MJ/vkm]; S = structure (shares of vehicle activity) [%]; and i is an index of vehicle modes and classes – MoMo models vehicles belonging to several modes. Vehicle activity can also be expressed as the product of vehicle stock [vehicles] and mileage [km/year]. The energy used by each mode and vehicle class in a given year [MJ/year] can, therefore, be calculated as the product of three main variables: vehicle stock (S) [vehicles], mileage (M) [km/year] and fuel economy (FE) [MJ/vkm].

To ensure a consistent modelling approach is adopted across the modes, energy use is estimated based on stocks (via scrappage functions), utilisation (travel per vehicle), consumption (energy use per vehicle, i.e. fuel economy) and emissions (via fuel emission factors for CO_2 and pollutants on a vehicle and well-to-wheel basis) for all modes. Final energy consumption, as estimated by the “bottom-up” approach described above, is then validated against and calibrated as necessary to the IEA energy balances (IEA, 2015a).

Vehicle platform, components and technology costs

Detailed cost modelling for passenger light-duty vehicles (PLDVs) accounts for initial (base year) costs, asymptotic (i.e. fully learned-out) costs and an experience parameter that defines the shape of cost reductions. These three parameters define learning functions that are based on the number of cumulative units produced worldwide. Cost functions define various vehicle configurations, including vehicle component efficiency upgrades (e.g. improved tyres, A/C controls, etc.), material substitution and vehicle downsizing, conventional spark- and compression ignition engine improvements, conventional and plug-in hybrid powertrain configurations, batteries, electric motors and fuel cells. These configurations are added to a basic glider cost. The ratios of differences in vehicle technologies deployed in PLDVs are extrapolated to other road vehicle types (i.e. two- and three-wheelers and freight trucks).

The primary drivers of technological change in transport are assumptions on the cost evolution of the technology, and the policy framework incentivising adoption of the technology. Oil prices and the set of policies assumed can significantly alter technology penetration patterns. For each scenario, the model supports a comparison of marginal costs of technologies and aggregates to total cost across all modes and regions.

Infrastructure and fuel costs

As outlined in Box 1.4 of Chapter 1, MoMo estimates future (2010-2050) infrastructure costs according to scenario-based projections on modal activity and fuel use. Infrastructure cost estimates include capital costs, operations and maintenance, and reconstruction costs – split by geography according to the location of the investments into urban and non-urban regions. Fuel costs are also estimated based on scenario-specific projections of urban and non-urban consumption, and include all fuel types (fossil-derived fuels, biofuels, electricity and hydrogen).

Elasticities

Key elasticities have been included in MoMo from 2012. Price and income elasticities of fuel demand, for light-duty road (passenger) activity as well as road freight, based upon representative "consensus" literature values, are used to model vehicle activity and fuel consumption responses to changes in fuel prices – which are themselves driven by projections and policy scenarios (i.e. GHG or fuel taxes). Elasticities also enable vehicle ownership to vary according to fuel prices and income, as proxied by GDP per capita.

The 2015-16 updates for *ETP 2016* include an expanded treatment of the above elasticities to encompass the urban / non-urban split, and to include the potential for municipal level policies to reduce transport energy use.[3]

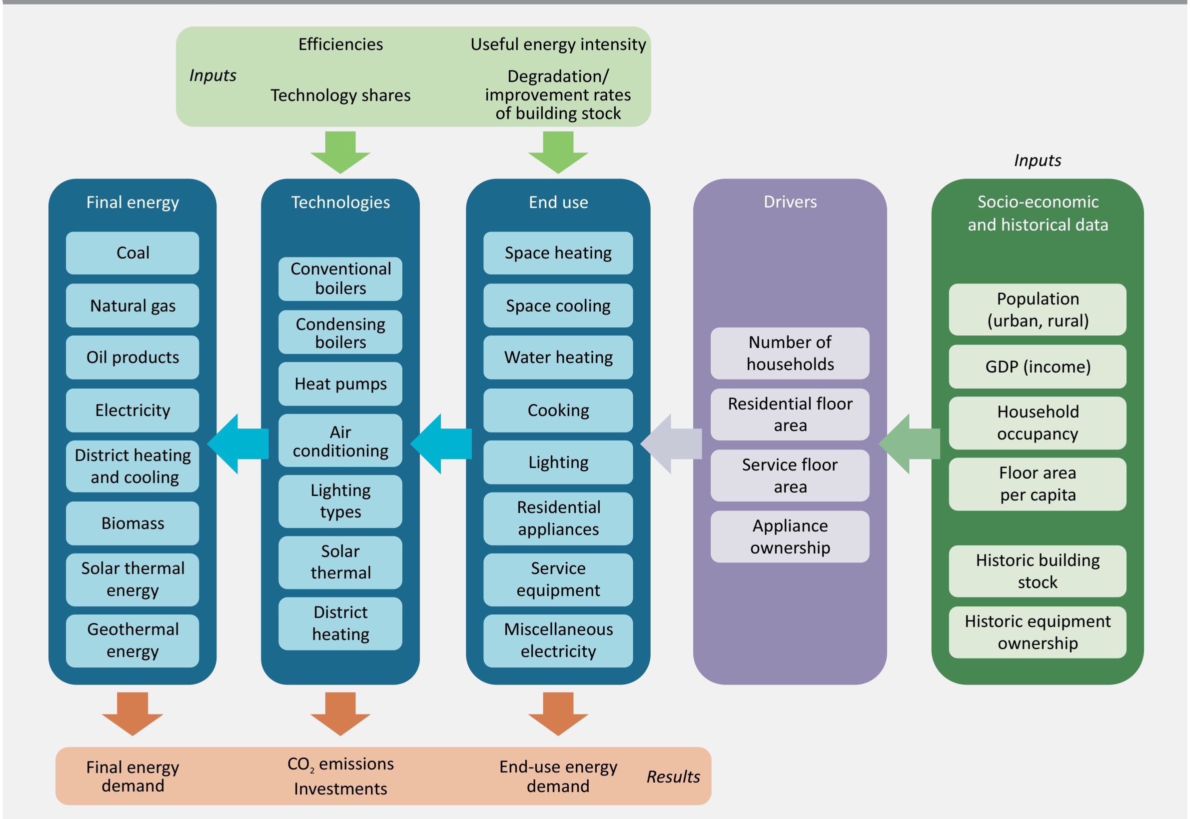
Buildings sector model

The buildings sector is modelled using a global simulation stock accounting model, split into the residential and services subsectors across 33 countries and regions (Figure A.6). The residential subsector includes all energy-using activities in apartments and houses, including space and water heating, cooling, lighting and the use of appliances and other electronic plug-loads. The services subsector includes activities related to trade, finance, real estate, public administration, health, food and lodging, education and other commercial services. This sub-sector is also commonly referred to as the commercial and public service sector. It covers energy used for space and water heating, cooling and ventilation, lighting and a number of other miscellaneous energy-consuming equipment such as commercial appliances, office equipment, cooking devices and medical equipment.

For both sub-sectors, the model uses socio-economic drivers, such as income (approximated by GDP) and population, to project the major building energy demand drivers, including residential and service floor space, number of households and residential appliance ownership. As far as possible, country statistics are used for historical floor area and appliance ownership rates. These data can be difficult to obtain across many developing countries, so in several cases the historical driver parameters for the buildings sector model have been estimated using a series of applied logistic functions relative to GDP per capita for the particular country or region. Building floor area is then differentiated by vintage, where approximations based on other indicators (e.g. historical population) are used to estimate the vintage distributions if no statistical data are available for a country or region.

3 Further details on the newly added national and municipal policies, the elasticities that are used to model transport activity, stock, and mode share responses to these policies, and the demand generation module can be found in annex F at www.iea.org/etp/etp2016/annexes.

Figure A.6 Structure of the buildings sector model



Key point *Starting from socio-economic assumptions, the buildings sector model determines demand drivers and the related useful energy demands, which are then applied across the building end-uses and technology choices to calculate final energy consumption across the 33 model regions.*

Differentiated stock accounting is used to estimate historical useful energy intensity across the various building end-uses with respect to assumed technology shares and efficiencies. Whenever possible, historical data on country/regional technology shares and efficiencies are applied. These useful energy intensities (e.g. demand for space heating per unit of floor area in terms of final delivered [i.e. useful] energy service) are then applied across the building end-uses with the projections for floor area, households and appliance ownership. The model takes into account the vintage of the building stock as well as the ageing or refurbishment of the buildings through corresponding degradation and improvement rates for the useful energy intensities.

For each of these derived useful energy demands, a suite of technology and fuel options are represented in the model, reflecting their current techno-economic characteristics (e.g. efficiencies) as well as their future improvement potential. Depending on the current technology stock as well as assumptions on the penetration and market shares of new technologies, the buildings sector model allows exploration of strategies that cover the different useful energy demands and the quantifying of the resulting developments for final energy consumption and related CO_2 emissions.

Framework assumptions

Economic activity (Table A.1) and population (Table A.2) are the two fundamental drivers of demand for energy services in *ETP* scenarios. These are kept constant across all scenarios as a means of providing a starting point for the analysis, and facilitating the interpretation of the results. Under the *ETP* assumptions, global GDP will more than triple between 2011 and 2050; uncertainty around GDP growth across the scenarios is significant, however. The climate change rate in the 6DS, and even in the 4°C Scenario (4DS), is likely to have profound negative impacts on the potential for economic growth. These impacts are not captured by *ETP* analysis. Moreover, the structure of the economy is likely to have non-marginal differences across scenarios, suggesting that GDP growth is unlikely to be identical even without considering secondary climate impacts. The redistribution of financial, human and physical capital will affect the growth potential both globally and on a regional scale.

Table A.1 Real GDP growth projections in *ETP 2016* (assumed identical across scenarios)

CAAGR (%)	2013-20	2020-30	2030-50	2013-50
World	3.7	3.8	2.8	3.2
OECD	2.2	2.0	1.6	1.8
Non-OECD	4.9	4.9	3.3	4.1
ASEAN	5.3	4.8	3.4	4.1
Brazil	1.4	3.9	2.8	2.8
China	6.5	5.3	2.7	4.1
European Union	1.9	1.8	1.5	1.6
India	7.5	6.6	4.5	5.6
Mexico	3.3	3.5	2.3	2.8
Russia	0.2	3.5	2.1	2.1
South Africa	2.3	2.9	2.5	2.6
United States	2.5	2.0	1.8	2.0

Notes: CAAGR = compounded average annual growth rate; ASEAN = Association of Southeast Asian Nations. Growth rates based on GDP in USD in purchase power parity (PPP) constant 2014 terms.
Source: IEA (2015b), *World Energy Outlook*; IMF (2015), World Economic Outlook Database, www.imf.org/external/pubs/ft/weo/2015/01/weodata/index.aspx.

Table A.2 Population projections used in *ETP 2016* (millions)

Country/Region	2013	2020	2030	2040	2050
World	7 102	7 652	8 354	8 962	9 468
OECD	1 265	1 312	1 367	1 403	1 425
Non-OECD	5 837	6 340	6 987	7 559	8 043
ASEAN	617	664	721	762	785
Brazil	200	211	223	229	231
China	1 386	1 433	1 453	1 435	1 385
European Union	524	532	538	538	536
India	1 252	1 353	1 476	1 566	1 620
Mexico	122	132	144	152	156
Russia	143	140	134	127	121
South Africa	53	55	58	61	63
United States	320	338	363	383	401

Source: UNDESA, (2014). *World Urbanization Prospects: The 2014 Revision*, http://esa.un.org/unpd/wup/.

Energy prices, including those of fossil fuels, are a central variable in the *ETP* analysis (Table A.3). The continuous increase in global energy demand is translated into higher prices of energy and fuels. Unless current demand trends are broken, rising prices are a likely consequence. However, the technologies and policies to reduce CO_2 emissions in the *ETP 2016* scenarios will have a considerable impact on energy demand, particularly for fossil fuels. Lower demand for oil in the 4DS and the 2DS means there is less need to produce oil from costly fields higher up the supply curve, particularly in non-members of the Organization of the Petroleum Exporting Countries (OPEC). As a result, oil prices in the 4DS and 2DS are lower than in the 6DS. In the 2DS, oil prices even slightly decline after 2030.

Prices for natural gas will also be affected, directly through downward pressure on demand, and indirectly through the link to oil prices that often exists in long-term gas supply contracts.[4] Finally, coal prices are also substantially lower owing to the large shift away from coal in the 2DS.

Table A.3 Fossil fuel prices by scenario

	Scenario	2014	2020	2025	2030	2035	2040	2045	2050
Oil (2014 USD/bbl)									
IEA crude oil import price	2DS	97	77	87	97	96	95	94	93
	4DS	97	80	97	113	121	128	133	137
	6DS	97	83	107	130	140	150	158	164
Coal (2014 USD/t)									
OECD steam coal import price	2DS	78	80	80	79	78	77	76	75
	4DS	78	94	98	102	105	108	111	114
	6DS	78	99	107	115	119	123	127	131
Gas (2014 USD/MBtu)									
US price	2DS	4.4	4.5	5.1	5.7	5.8	5.9	5.8	5.8
	4DS	4.4	4.7	5.5	6.2	6.9	7.5	7.8	8.0
	6DS	4.4	4.7	5.5	6.3	7.1	7.8	8.2	8.5
Europe import price	2DS	9.3	7.5	8.5	9.4	9.2	8.9	8.8	8.7
	4DS	9.3	7.8	9.5	11.2	11.8	12.4	12.9	13.3
	6DS	9.3	8.1	10.3	12.5	13.2	13.8	14.5	15.1
Japan import price	2DS	16.2	10.7	11.3	11.8	11.5	11.1	11.0	10.9
	4DS	16.2	11.0	12.0	13.0	13.6	14.1	14.7	15.1
	6DS	16.2	11.4	13.2	14.9	15.5	16.0	16.9	17.5

Notes: bbl = barrel; t = tonne; MBtu = million British thermal units.

4 This link is assumed to become weaker over time in the ETP analysis, as the price indexation business model is gradually phased out in international markets.

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Abbreviations and Acronyms

A

AC	alternating current
AIDC	automatic identification and data capture
AMI	advanced metering infrastructure
ASEAN	Association of Southeast Asian Nations
ATAG	Air Transport Action Group

B

BAT	best available technology
BAU	business-as-usual
BEA	buildings efficiency accelerator
BEV	battery electric vehicle
BF	blast furnace
BOF	basic oxygen furnace
BRT	bus rapid transit
BTX	benzene, toluene and xylene

C

CAD	Canadian dollar
CCS	carbon capture and storage
CDD	cooling degree days
CDQ	coke dry quenching
CEMS	community energy management system
CfD	contract for difference
CFL	compact fluorescent lamp
CHP	combined heat and power
CM	clean energy generation measures
CNG	compressed natural gas
CNY	Chinese yuan
CONAPO	*Consejo Nacional de Población*
CSP	concentrated solar power
CTCN	Climate Technology Centre and Network

D

DECC	UK Department of Energy and Climate Change
DG	distributed generation
DHC	district heating and cooling
DR	demand response
DSO	distribution system operator
DTC	direct-to-consumer

E

EAF	electric arc furnace
ECOCASA	*Programa de Cooperación Financiera para la oferta de Vivienda Sustentable en Mexico*
EEA	European Energy Award
EESL	energy efficiency standards and labelling
EIB	European Investment Bank
EJ	exajoule
EMS	energy management system
ENS	Danish Energy Agency
EOR	enhanced oil recovery
EPC	energy performance contracting
ESCII	energy sector carbon intensity index
ESCO	energy service company
ESU	energy service utility
ETP	*Energy Technology Perspectives*
ETP	Energy Technology and Policy
EU	European Union
EV	electric vehicle

F

FCEV	fuel cell electric vehicle
FCM	Federation of Canadian Municipalities
FIT	feed-in tariff
FMVM	*Fondo Metropolitano* of the Valley of Mexico
FQD	Fuel Quality Directive
FYP	Five-Year Plan

G

GDP	gross domestic product
GHG	greenhouse gas
GMF	Green Municipal Fund
GPS	global positioning system
GTZ	*Deutsche Gesellschaft für Technische Zusammenarbeit*
GW	Gigawatt

H

HDD	heating degree day
HFT	heavy freight truck
HSR	high-speed rail
HVAC	heating, ventilation and air conditioning
HVDC	high-voltage direct current

I

IADB	Inter-American Development Bank
ICAO	International Civil Aviation Organisation
ICE	internal combustion engine
ICLEI	International Council for Local Environmental Initiatives
ICT	information and communication technologies
IEA	International Energy Agency

IEH	industrial excess heat
IFC	International Finance Corporation
IIP	Institute for Industrial Productivity
INDC	intended nationally determined contribution
INECC	*Instituto Nacional de Ecología y Cambio Climático*
INEGI	*Instituto Nacional de Estadistica y Geografia*
INR	Indian rupee
IRENA	International Renewable Energy Agency
ITC	investment tax credit
ITS	intelligent transport systems
IUS	Integrated Utility Services

J

JISF	Japanese Iron and Steel Federation

K

KfW	*Kreditanstalt für Wiederaufbau*

L

LCFS	low-carbon fuel standard
LCOE	levelised cost of electricity
LCV	light commercial vehicle
LDV	light-duty vehicle
LED	light-emitting diode
LEED	Leadership in Energy and Environmental Design
LMI	low and middle income
LNG	liquefied natural gas
LPAA	Lima Paris Action Agenda
LPG	liquefied petroleum gas
LUC	land-use change

M

MaaS	mobility as a service
MEA	Ministry of External Affairs of India
MEPS	minimum energy performance standards
MF	Metropolitan Fund
MFT	medium freight trucks
MRV	measurement, reporting and verification
MSW	municipal solid waste
MTR	Mass Transit Railway
MTRMR	*Medium-Term Renewable Energy Market Report*
MUSH	municipalities, universities, schools and hospitals

N

NAMA	nationally appropriate mitigation action
NDC	nationally determined contributions
NEA	Nuclear Energy Agency
NER	Nordic Energy Research
NGO	non-governmental organisation

	NMX	*Norma Mexicana*
	NOM	*Norma Oficial Mexicana*
	NZD	New Zealand dollar
O	O&M	operation and maintenance
	OECD	Organisation for Economic Co-operation and Development
	OLTC	on-load tap changer
	ORC	organic Rankine cycles
P	PACE	property-assessed clean energy
	PAT	perform, achieve and trade
	PECC	*Programa Especial de Cambio Climático*
	PHEV	plug-in hybrid electric vehicle
	PJ	petajoule
	PLDV	passenger light-duty vehicle
	PND	*Plan Nacional de Desarrollo*
	PNDU	*Plan Nacional de Desarrollo Urbano*
	PNV	*Plan Nacional de Vivienda*
	PPA	power purchase agreement
	PPP	public-private partnership
	PRIS	power reactor information system
	PROTRAM	*Programa Federal de Apoyo al Transporte Urbano Masivo*
	PTC	production tax credit
	PV	photovoltaic
R	R&D	research and development
	RD&D	research, development and demonstration
	RDD&D	research, development, demonstration and deployment
	RDF	refuse-derived fuel
	RESNET	Residential Energy Services Network
	RGGI	Regional Greenhouse Gas Initiative
	RMI	Rocky Mountain Institute
	RTSPV	rooftop solar photovoltaics
S	SCADA	supervisory control and data acquisition
	SEDATU	*Secretaría de Desarrollo Agrario, Territorial y Urbano*
	SEMARNAT	*Secretaría de Medio Ambiente y Recursos Naturales*
	SENER	*Secretaria de Energia de Mexico*
	SEP	sustainable energy plans
	SEU	sustainable energy utility
	SHF	Sociedad Hipotecaria Federal
	SMG	Seoul Metropolitan Government
	SNBHBP	Swedish National Board of Housing, Building and Planning
	STE	solar thermal energy
	SVR	step voltage regulators

T

T&D	transmission and distribution
TCP	Technology Collaboration Programme
TDM	travel demand management
TFC	total final energy consumption
TNA	technology needs assessment
TPES	Total Primary Energy Supply
TSO	Transmission Systems Operator
TURN	Technologies and Urban Resource Networks

U

UCLG	United Cities and Local Governments
UITP	International Association of Public Transport
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States dollars

V

VPP	virtual power plants
VRE	variable renewable energy

W

WEPP	World Electric Power Plant
WHO	World Health Organization
WRI	World Resources Institute
WTE	waste-to-energy
WTW	well-to-wheel
WWT	wastewater treatment

Y

YSCP	Yokohama Smart City Project

Z

ZEB	zero-energy building

Definitions, Regional and Country Groupings and Units

Definitions

2-, 3- and 4-wheelers: This vehicle category includes motorised vehicles having two, three or four wheels. 4-wheelers are not homologated to drive on motorways, such as all-terrain vehicles. Most often, 2- and 3-wheelers are reported as an aggregated class.

A

Advanced biofuels: Advanced biofuels comprise different emerging and novel conversion technologies that are currently in the research and development, pilot or demonstration phase. This definition differs from the one used for "advanced biofuels" in the US legislation, which is based on a minimum 50% life-cycle greenhouse gas (GHG) reduction and which, therefore, includes sugar cane ethanol.

Aquifer: A porous, water-saturated body of rock or unconsolidated sediments, the permeability of which allows water to be produced (or fluids injected). If the water contains a high concentration of salts, it is a saline aquifer.

B

Biodiesel: Biodiesel is a diesel-equivalent, processed fuel made from the transesterification (a chemical process which, in this case, refers to the removal of glycerine from the oil) of both vegetable oils and animal fats.

Bioenergy: Bioenergy is material which is directly or indirectly produced by photosynthesis and which is utilised as a feedstock in the manufacture of fuels and substitutes for petrochemical and other energy intensive products.

Biofuels: Biofuels are fuels derived from biomass or waste feedstocks and include ethanol and biodiesel. They can be classified as conventional and advanced biofuels according to the technologies used to produce them and their respective maturity.

Biogas: Biogas is a mixture of methane and CO_2 produced by bacterial degradation of organic matter and used as a fuel.

Biomass: Biological material that can be used as fuel or for industrial production. Includes solid biomass such as wood, plant and animal products, gases and liquids derived from biomass, industrial waste and municipal waste.

Biomass and waste: Biomass and waste includes solid biomass, gas and liquids derived from biomass, industrial waste and the renewable part of municipal waste. Includes both traditional and modern biomass.

Biomass-to-liquids	Biomass-to-liquids (BTL) refers to a process that gasifies biomass to produce syngas (a mixture of hydrogen and carbon monoxide), followed by synthesis of liquid products (such as diesel, naphtha or gasoline) from the syngas using Fischer-Tropsch catalytic synthesis or a methanol-to-gasoline reaction path. The process is similar to those used in coal-to-liquids or gas-to-liquids.
Bio-SNG	Bio-synthetic natural gas (BIO-SNG) is biomethane derived from biomass via thermal processes.
Black liquor	A by-product from chemical pulping processes, which consists of lignin residue combined with water and the chemicals used for the extraction of the lignin.
Bond market/bonds	Bond is a formal contract to repay borrowed money with interest at fixed intervals.
Benzene, toluene and xylene	Benzene, toluene and xylene (BTX), also referred to as aromatics, are a major group of products from the petrochemicals sector.
Buses and minibuses	Passenger motorised vehicles with more than nine seats.

C

Capacity credit	Capacity credit refers to the proportion of capacity that can be reliably expected to generate electricity during times of peak demand in the grid to which it is connected.
Capacity (electricity)	Measured in megawatts (MW), capacity (electricity) is the amount of power produced, transmitted, distributed or used at a given moment.
Carbon capture and storage	A process in which CO_2 is separated from a mixture of gases (e.g. the flue gases from a power station or a stream of CO_2-rich natural gas) and compressed to a liquid state; transported to a suitable storage site; and injected into a geologic formation where it is retained by natural trapping mechanisms and monitored as necessary.
Clinker	Clinker is a core component of cement made by heating ground limestone and clay at a temperature of about 1 400°C to 1 500°C.
CO_2 emissions	CO_2 emissions in the *ETP* analysis include, if not noted otherwise, emissions from energy use and process emissions (industry, gas processing). If a fossil fuel is used as a raw material (or feedstock) for manufacture of products such as plastics or in a non-energy use (e.g. bitumen for road construction), only some of the carbon in the fossil fuel is oxidised to CO_2. These CO_2 emissions from feedstock or non-energy use are included in the *ETP* analysis. Combustion of biofuels is considered to be carbon-free, except in the analysis of the well-to-wheel GHG emissions for the transport sector, which includes literature estimates for direct land-use change emissions (but excludes indirect land-use change emissions). CO_2 emissions from land use, land-use change and forestry (LULUCF) are not included in the *ETP* analysis.
Coal	Coal includes both primary coal (including hard coal and brown coal) and derived fuels (including patent fuel, brown-coal briquettes, coke-oven coke, gas coke, gas-works gas, coke-oven gas, blast-furnace gas and oxygen steel furnace gas). Peat is also included.

	Coal-to-liquids	Coal-to-liquids (CTL) refers to the transformation of coal into liquid hydrocarbons. It can be achieved through either coal gasification into syngas (a mixture of hydrogen and carbon monoxide), combined with Fischer-Tropsch or methanol-to-gasoline synthesis to produce liquid fuels, or through the less developed direct-coal liquefaction technologies in which coal is directly reacted with hydrogen.
	Coefficient of performance	Coefficient of performance is the ratio of heat output to work supplied, generally applied to heat pumps as a measure of their efficiency.
	Co-generation	Co-generation refers to the combined production of heat and power.
	Coking coal	Coking coal, also known as metallurgical coal, is used to create coke, an essential ingredient for the production of steel. Coking coal exhibits qualities that allow the coal to soften, liquefy and then re-solidify into hard but porous lumps when heated in the absence of air. Coking coal must also have low sulphur and phosphorous contents.
	Conventional biofuels	Conventional biofuels include well-established technologies that are producing biofuels on a commercial scale today. These biofuels are commonly referred to as first-generation and include sugar cane ethanol, starch-based ethanol, biodiesel, Fatty Acid Methyl Esther (FAME) and Straight Vegetable Oil (SVO). Typical feedstocks used in these mature processes include sugar cane and sugar beet, starch-bearing grains like corn and wheat, oil crops like canola and palm, and in some cases animal fats.
D	Demand response	Demand response is a mechanism by which electricity demand is shifted over given time periods in response to price changes or other incentives, but does not necessarily reduce overall electrical energy consumption. This can be used to reduce peak demand and provide electricity system flexibility.
	Direct equity investment	Direct equity investments refer to the acquisition of equity (or shares) in a company.
	Distribution	Electricity distribution systems transport electricity from the transmission system to end users.
	Electric arc furnace (EAF)	Electric arc furnaces are used as a less energy-intensive alternative to the traditional blast furnace-basic oxygen furnace steelmaking process route, when the necessary material inputs are available. Steel is formed by creating an electric arc to melt scrap metal or direct reduced iron.
E	Electrical energy	Measured in megawatt-hours (MWh) or kilowatt-hours (kWh), indicates the net amount of electricity generated, transmitted, distributed or used over a given time period.
	Electricity generation	Electricity generation is defined as the total amount of electricity generated by power only or co-generation (combined heat and power) plants including generation required for own use. This is also referred to as gross generation.

Energy intensity	A measure where energy is divided by a physical or economic denominator, e.g. energy use per unit of GDP or energy use per tonne of cement.
Enhanced oil recovery (EOR)	Enhanced oil recovery (EOR) is a tertiary recovery process that modifies the properties of oil in a reservoir to increase recovery of oil, examples of which include: surfactant injection, steam injection, hydrocarbon injection, and CO_2 flooding. EOR is typically used following primary recovery (oil produced by the natural pressure in the reservoir) and secondary recovery (using water injection).
Ethanol	Although ethanol can be produced from a variety of fuels, in this book ethanol refers to bio-ethanol only. Ethanol is produced from fermenting any biomass high in carbohydrates. Today, ethanol is usually made from starches and sugars, but second-generation technologies allow it to be made from cellulose and hemicellulose, the fibrous material that makes up the bulk of most plant matter.

F

Fischer-Tropsch (FT) synthesis	Catalytic production process for the production of synthetic fuels. Natural gas, coal and biomass feedstocks can be used.
Flexibility	Power system flexibility expresses the extent to which a power system can modify electricity production or consumption in response to variability, expected or otherwise. In other words, it expresses the capability of a power system of maintaining reliable supply in the face of rapid and large imbalances, whatever the cause. It is measured in terms of the MW available for ramping up and down, over time (±MW/time).
Fuel cell	A device that can be used to convert hydrogen or natural gas into electricity. Various types exist that can be operated at temperatures ranging from 80°C to 1 000°C. Their efficiency ranges from 40% to 60%. For the time being, their application is limited to niche markets and demonstration projects due to their high cost and the immature status of the technology, but their use is growing fast.

G

Gas	Gas includes natural gas, both associated and non-associated with petroleum deposits, but excludes natural gas liquids.
Gas-to-liquids	Gas-to-liquids (GTL) refers to a process featuring reaction of methane with oxygen or steam to produce syngas (a mixture of hydrogen and carbon monoxide) followed by synthesis of liquid products (such as diesel and naphtha) from the syngas using Fischer-Tropsch catalytic synthesis. The process is similar to those used in coal-to-liquids or biomass-to-liquids.

H

Heat	Heat is obtained from the combustion of fuels, nuclear reactors, geothermal reservoirs, capture of sunlight, exothermic chemical processes and heat pumps which can extract it from ambient air and liquids. It may be used for domestic hot water, space heating or cooling, or industrial process heat. In IEA statistics, heat refers to heat produced for sale only. Most heat included in this category comes from the combustion of fuels in co-generation installations, although some small amounts are produced from geothermal sources, electrically powered heat pumps and boilers. Heat produced for own use, for example in buildings and industry processes, is not included in IEA statistics, although frequently discussed in this book.

	Hydropower	Hydropower refers to the energy content of the electricity produced in hydropower plants, assuming 100% efficiency. It excludes output from pumped storage and marine (tide and wave) plants.
I	Industrial excess heat (IEH)	IEH can be defined as the heat content of all streams leaving an industrial process at a given moment in time. The extent to which heat can be technically and economically recovered depends on the characteristics of the heat sources and the availability of a compatible end use.
	Integrated gasification combined-cycle (IGCC)	Integrated gasification combined-cycle (IGCC) is a technology in which a solid or liquid fuel (coal, heavy oil or biomass) is gasified, followed by use for electricity generation in a combined-cycle power plant.
L	Liquidity	Liquidity is the ability to sell assets without significant movement in the price and with minimum loss of value.
	Low-carbon energy technologies	Energy technologies that emit less CO_2 (in comparison with conventional sources) from all sectors (buildings, industry, power and transport) that are being pursued in an effort to mitigate climate change.
M	Markets	Markets are structures which allow buyers and sellers to exchange any type of goods, services and information.
	Middle distillates	Middle distillates include jet fuel, diesel and heating oil.
	Modern biomass	Modern biomass includes all biomass with the exception of traditional biomass.
N	Non-energy use	Non-energy use refers to fuels used for chemical feedstocks and non-energy products. Examples of non-energy products include lubricants, paraffin waxes, coal tars and oils as timber preservatives.
	Nuclear	Nuclear refers to the primary heat equivalent of the electricity produced by a nuclear plant with an average thermal efficiency of 33%.
O	Oil	Oil includes crude oil, condensates, natural gas liquids, refinery feedstocks and additives, other hydrocarbons (including emulsified oils, synthetic crude oil, mineral oils extracted from bituminous minerals such as oil shale, bituminous sand and oils from coal liquefaction) and petroleum products (refinery gas, ethane, LPG, aviation gasoline, motor gasoline, jet fuels, kerosene, gas/diesel oil, heavy fuel oil, naphtha, white spirit, lubricants, bitumen, paraffin waxes and petroleum coke).
	Options	Options are instruments that convey the rights, but not the obligation, to engage in a future transaction on an underlying security or in a future contract.
P	Passenger light-duty vehicles	This vehicle category includes all four-wheel road vehicles aimed at the mobility of persons on all types of roads, up to nine persons per vehicle and 3.5 t of gross vehicle weight.

	Private equity	Private equity is money invested in companies that are not publicly traded on a stock exchange or invested as part of buyouts of publicly traded companies in order to make them private companies.
	Process CO_2 emissions	Process emissions refer to the portion of CO_2 emissions that are inherently generated by the reactions taking place in an industrial process, such as CO_2 released during calcination of limestone in cement kilns.
	Project finance	Project finance is the financing of long-term infrastructure, industrial projects and public services, based upon a non-recourse or limited recourse financial structure where project debt and equity used to finance the project are paid back from the cash flow generated by the project.
	Purchasing power parity (PPP)	Purchasing power parity (PPP) is the rate of currency conversion that equalises the purchasing power of different currencies. It makes allowance for the differences in price levels and spending patterns between different countries.
R	Renewables	Renewable energy sources (renewables) include biomass and waste, geothermal, hydropower, solar photovoltaic, concentrating solar power, wind and marine (tide and wave) energy for electricity and heat generation.
S	Steam coal	All other hard coal that is not classified as coking coal. Also included are recovered slurries, middlings and other low-grade coal products not further classified by type. Coal of this quality is also commonly known as thermal coal.
	Synthetic fuels	Synthetic fuel or synfuel is any liquid fuel obtained from coal, natural gas or biomass. The best known process is the Fischer-Tropsch synthesis. An intermediate step in the production of synthetic fuel is often syngas, a mixture of carbon monoxide and hydrogen produced from coal which is sometimes directly used as an industrial fuel.
T	Total final consumption (TFC)	TFC is the sum of consumption by the different end-use sectors, it excludes conversion losses from the transformation sector (power plants, oil refineries, etc.), energy industry own energy use and other losses. TFC is broken down into energy demand in the following sectors: industry (including manufacturing and mining), transport, buildings (including residential and services) and other (including agriculture and non-energy use). In the *ETP* scenarios, the final consumption of the transport sector on a regional or national level includes international marine and aviation bunkers, but not pipeline transport, which is included under energy-industry own energy use. Energy use from blast furnaces and coke ovens is included in the final consumption of the industry sector.
	Total primary energy demand	Total primary energy demand (TPED) represents domestic demand only and is broken down into power generation, other energy sector and total final consumption. Deviating from this IEA definition, *ETP* results at regional or national level also include primary energy demand from international aviation and shipping.

Total primary energy supply	Total primary energy supply (TPES) is equivalent to total primary energy demand. TPES represents inland demand only and, except for world energy demand, excludes international marine and aviation bunkers. Deviating from this IEA definition, *ETP* results at regional or national level also include primary energy use for international aviation and shipping.
Traditional use of biomass	Traditional use of biomass refers to the use of fuel wood, charcoal, animal dung and agricultural residues for cooking and heating in the residential sector. It tends to have very low conversion efficiency (10% to 20%) and often unsustainable biomass supply.
Transmission	Electricity transmission systems transfer electricity from generation (from all types, such as variable and large-scale centralised generation, and large-scale hydro with storage) to distribution systems (including small and large consumers) or to other electricity systems.

Sector definitions

Buildings	The buildings sector (buildings) includes energy used in residential, commercial and public buildings. Buildings energy use includes space heating and cooling, water heating, lighting, appliances, cooking and miscellaneous equipment (such as office equipment and other small plug loads in the residential and service sectors).
Energy industry own use	Energy industry own use covers energy used in coal mines, in oil and gas extraction and in electricity and heat production. Transfers and statistical differences as well as pipeline transport are also included in this category.
Fuel transformation	Fuel transformation covers the use of energy by transformation sectors and the energy losses in converting primary energy into a form that can be used in final consuming sectors. It includes losses by gas works, petroleum refineries, coal and gas transformation and liquefaction as well as biofuel and hydrogen production. Energy use in blast furnaces, coke ovens and petrochemical plants is not included, but accounted for in the industry sector.
Industry	The industry sector includes fuel used within the mining (excluding energy-producing industries), manufacturing and construction sectors. Fuel used as petrochemical feedstock and in coke ovens and blast furnaces is also included. Key industry sectors include iron and steel, chemical and petrochemical, non-metallic minerals, non-ferrous metals and pulp and paper. Use by industries for the transformation of energy into another form or for the production of fuels is excluded and reported separately under fuel transformation. Consumption of fuels for the transport of goods is reported as part of the transport sector.
Other end uses	Other end uses refer to final energy used in agriculture, forestry and fishing as well as other non-specified consumption.
Power generation	Power generation refers to fuel use in electricity plants, heat plants and co-generation plants. Both main activity producer plants and so-called autoproducer plants that produce electricity or heat for their own use are included.
Transport	The transport sector comprises all major motorised modes, including domestic marine and aviation activity and international marine and aviation bunkers, the latter being allocated among countries based on available statistics. Tank-to-wheel emissions cover all the energy used once transformed, while well-to-tank emissions are based on attributional life-cycle assessment studies of fossil-derived fuels (e.g. gasoline, diesel, compressed and liquefied natural gas), biofuels and electricity (based on time- and scenario-specific estimated average grid carbon intensity). Energy use and emissions resulting from pipeline transport are accounted for under "Energy industry own use".

Regional and country groupings

Africa	Algeria, Angola, Benin, Botswana, Cameroon, Congo, Democratic Republic of Congo, Côte d'Ivoire, Egypt, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Libya, Morocco, Mozambique, Namibia, Nigeria, Senegal, South Africa, Sudan,[1] United Republic of Tanzania, Togo, Tunisia, Zambia, Zimbabwe and other African countries and territories.[2]
ASEAN (Association of Southeast Asian Nations)	Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Myanmar, Philippines, Singapore, Thailand and Viet Nam.
Asia	Bangladesh, Brunei Darussalam, Cambodia, China, India, Indonesia, Japan, Korea, the Democratic People's Republic of Korea, Malaysia, Mongolia, Myanmar, Nepal, Pakistan, Philippines, Singapore, Sri Lanka, Chinese Taipei, Thailand, Viet Nam and other Asian countries and territories.[3]
China	Refers to the People's Republic of China, including Hong Kong.
Economies in Transition (EITs)	Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus,[4] Former Yugoslav Republic of Macedonia, Georgia, Gibraltar, Kazakhstan, Republic of Kosovo, Kyrgyz Republic, Latvia, Lithuania, Republic of Moldova, Montenegro, Romania, the Russian Federation, Serbia, Tajikistan, Turkmenistan, Ukraine and Uzbekistan.
European Union	Austria, Belgium, Bulgaria, Croatia, Cyprus,[5] Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden and the United Kingdom.
Latin America	Argentina, Bolivia, Brazil, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Trinidad and Tobago, Uruguay, Venezuela and other Latin American countries and territories.[6]
Middle East	Bahrain, the Islamic Republic of Iran, Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates and Yemen. It includes the neutral zone between Saudi Arabia and Iraq.
OECD	Includes OECD Europe, OECD Americas and OECD Asia Oceania regional groupings.
OECD Americas	Canada, Chile, Mexico and the United States.

1 Because only aggregated data were available until 2011, the data for Sudan also include South Sudan.
2 Individual data are not available for: Burkina Faso, Burundi, Cabo Verde, Central African Republic, Chad, Comoros, Djibouti, Equatorial Guinea, Gambia, Guinea, Guinea-Bissau, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Niger, Reunion, Rwanda, Sao Tome and Principe, Seychelles, Sierra Leone, Somalia, Swaziland, Uganda and Western Sahara (territory). Data are estimated in aggregate for these regions.
3 Individual data are not available for: Afghanistan, Bhutan, Cook Islands, Timor-Leste, Fiji, French Polynesia, Kiribati, Lao PDR, Macau, Maldives, New Caledonia, Palau, Papua New Guinea, Samoa, Solomon Islands, Tonga and Vanuatu. Data are estimated in aggregate for these regions.
4 1. Footnote by Turkey: The information in this document with reference to "Cyprus" relates to the southern part of the Island. There is no single authority representing both Turkish and Greek Cypriot people on the Island. Turkey recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Turkey shall preserve its position concerning the "Cyprus issue".
2. Footnote by all the European Union Member States of the OECD and the European Union: The Republic of Cyprus is recognised by all members of the United Nations with the exception of Turkey. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.
5 See note 4.
6 Individual data are not available for: Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bermuda, British Virgin Islands, Cayman Islands, Dominica, Falkland Islands (Malvinas), French Guyana, Grenada, Guadeloupe, Guyana, Martinique, Montserrat, St. Kitts and Nevis, Saint Lucia, Saint Pierre et Miquelon, St. Vincent and the Grenadines, Suriname and Turks and Caicos Islands. Data are estimated in aggregate for these regions.

OECD Asia Oceania	Includes OECD Asia, comprising Japan, Korea and Israel,[7] and OECD Oceania, comprising Australia and New Zealand.
OECD Europe	Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey and the United Kingdom.
Other developing Asia	Non-OECD Asia regional grouping excluding China and India.
Deviating regional definition only used for Figure 2.54	**Asia Pacific:** Afghanistan, American Samoa, Armenia, Australia, Azerbaijan, Bangladesh, Bhutan, British Indian Ocean Territory, Brunei Darussalam, Cambodia, People's Republic of China, Christmas Island (Indian Ocean), Cocos (Keeling) Islands, Comoros, Cook Islands, Fiji, French Polynesia, Guam, Heard and McDonald Islands, Hong Kong (China), India, Indonesia, Japan, Kazakhstan, Kiribati, Korea, the Democratic People's Republic of Korea, Kyrgyzstan, Lao People's Democratic Republic, Malaysia, Maldives, Marshall Islands, Mayotte, Federated States of Micronesia, Midway Islands, Mongolia, Myanmar, Nauru, Nepal, New Caledonia, New Zealand, Niue, Norfolk Island, Northern Mariana Islands, Pakistan, Palau, Papua New Guinea, Paracel Islands, Philippines, Pitcairn, Samoa, Seychelles, Singapore, Solomon Islands, Spratly Island, Sri Lanka, Chinese Taipei, Tajikistan, Thailand, Tokelau, Tonga, Turkmenistan, Tuvalu, Uzbekistan, Vanuatu, Viet Nam, Wake Island, Wallis and Futuna Islands.
	Europe: Albania, Andorra, Austria, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus,[8] Czech Republic, Denmark, Estonia, Faroe Islands, Finland, Former Yugoslav Republic of Macedonia, France, Georgia, Germany, Gibraltar, Greece, Guernsey, Hungary, Iceland, Ireland, Isle of Man, Italy, Jersey, Republic of Kosovo, Latvia, Liechtenstein, Lithuania, Luxembourg, Malta, Republic of Moldova, Monaco, Montenegro, Netherlands, Norway, Poland, Portugal, Romania, Russian Federation, San Marino, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine, United Kingdom.
	Latin America: Anguilla, Antigua and Barbuda, Argentina, Aruba, Bahamas, Barbados, Belize, Bermuda Islands, Bolivia, Bouvet Island, Brazil, British Virgin Islands, Cabo Verde, Cayman Islands, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, Falkland Islands (Malvinas), French Guiana, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Montserrat, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Saint Helena, St. Kitts-Nevis, Saint Lucia, Saint Pierre and Miquelon, St. Vincent and the Grenadines, South Georgia and the South Sandwich Islands, Suriname, Trinidad and Tobago, Turks and Caicos Islands, Uruguay, Venezuela, Virgin Islands of the United States, West Indies.
	Middle East/Africa: Algeria, Angola, Bahrain, Botswana, Burkina Faso, Burundi, Cameroon, Central African Public, Chad, Congo, Democratic Republic of the Congo, Cote d'Ivoire, Djibouti, Egypt, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, the Islamic Republic of Iran, Iraq, Israel, Jordan, Kenya, Kuwait, Lebanon, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Morocco, Mozambique, Namibia, Niger, Nigeria, Oman, Palestinian Authority, Qatar, Réunion, Rwanda, Sao Tome and Principe, Saudi Arabia, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Syrian Arab Republic, United Republic of Tanzania, Togo, Tunisia, Turkey, Uganda, United Arab Emirates, Western Sahara (territory), Yemen, Zambia, Zimbabwe.
	North America: Canada, Greenland, United States.

7 The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD and/or the IEA is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

8 See note 4.

Units of measure

Unit prefix	E	exa (10^{18}, quintillion)
	P	peta (10^{15}, quadrillion)
	T	tera (10^{12}, trillion)
	G	giga (10^{9}, billion)
	M	mega (10^{6}, million)
	k	kilo (10^{3}, thousand)
	c	centi (10^{-2}, hundredth)
	m	milli (10^{-3}, thousandth)
	μ	micro (10^{-6}, millionth)
Area	ha	hectare
	km^2	square kilometre
	m^2	square metre
Coal	Mtce	million tonnes of coal equivalent (equals 0.7 Mtoe)
Emissions	ppm	parts per million (by volume)
	$GtCO_2$-eq	gigatonnes of carbon-dioxide equivalent (using 100-year global warming potentials for different greenhouse gases)
	$kgCO_2$-eq	kilogrammes of carbon-dioxide equivalent
	gCO_2/km	grammes of carbon dioxide per kilometre
	gCO_2/kWh	gramme of carbon dioxide per kilowatt-hour
Energy	Boe	barrel of oil equivalent
	toe	tonne of oil equivalent
	ktoe	thousand tonnes of oil equivalent
	Mtoe	million tonnes of oil equivalent
	MBtu	million British thermal units
	Kcal	kilocalorie (1 calorie x 10^{3})
	Gcal	gigacalorie (1 calorie x 10^{9})
	MJ	megajoule (1 joule x 10^{6})
	GJ	gigajoule (1 joule x 10^{9})
	TJ	terajoule (1 joule x 10^{12})
	PJ	petajoule (1 joule x 10^{15})
	EJ	exajoule (1 joule x 10^{18})
	kWh	kilowatt-hour
	MWh	megawatt-hour
	GWh	gigawatt-hour
	TWh	terawatt-hour

Gas	mcm	million cubic metres
	bcm	billion cubic metres
	tcm	trillion cubic metres
	scf	standard cubic foot
	kg	kilogramme
	kt	kilotonnes (1 tonne x 10^3)
	Mt	million tonnes (1 tonne x 10^6)
	t	tonne
Monetary	USD billion	1 US dollar x 10^9
	USD trillion	1 US dollar x 10^{12}
Oil	b/d	barrel per day
	kb/d	thousand barrels per day
	mb/d	million barrels per day
	mboe/d	million barrels of oil equivalent per day
Power	W	watt (1 joule per second)
	kW	kilowatt (1 watt x 10^3)
	MW	megawatt (1 watt x 10^6)
	GW	gigawatt (1 watt x 10^9)
	TW	terawatt (1 watt x 10^{12})
Transport	km	kilometre
	km/hr	kilometre per hour
	lge	litre of gasoline-equivalent
	mpg	mile per gallon
	pkm	passenger kilometre
	tkm	tonne kilometre
	vkm	vehicle kilometre

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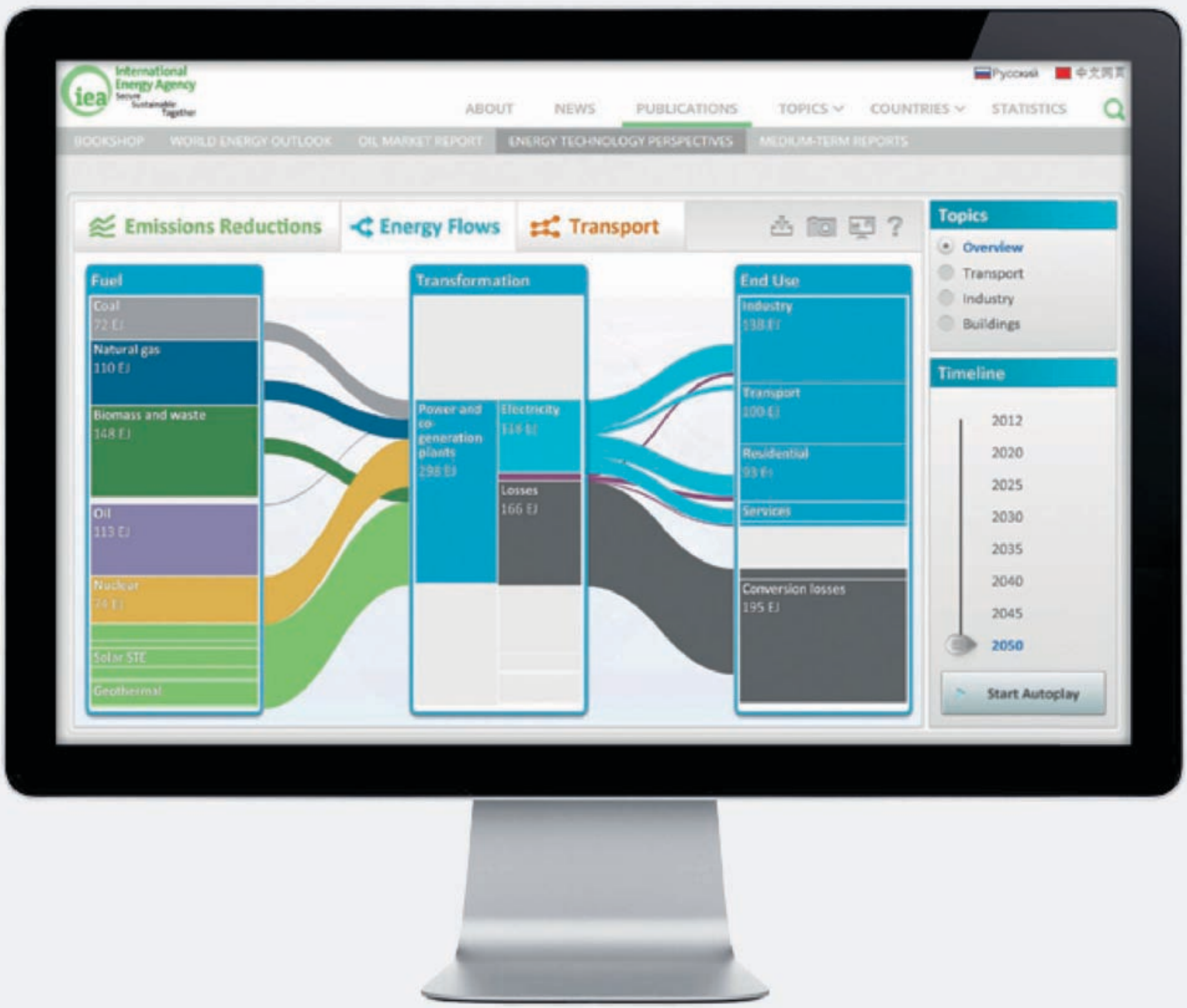

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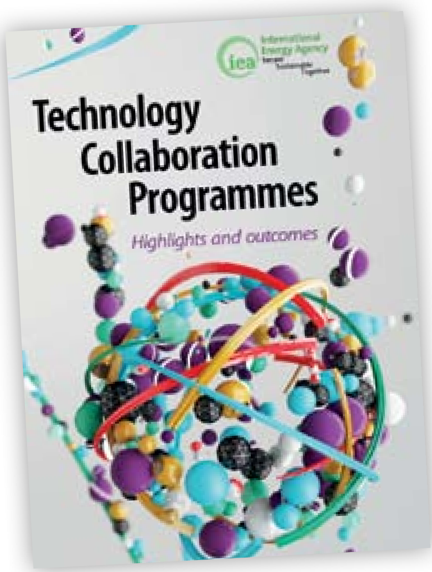

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Energy Technology Perspectives 2016

Towards Sustainable Urban Energy Systems

Cities drive economic growth but can also drive sustainable change. As the share of the world's population living in cities rises, ambitious action in urban areas can be instrumental in achieving long term sustainability of the global energy system – including the carbon emission reductions required to meet the climate goals reached at COP21 in Paris. Support from national governments is a strategic prerequisite for leveraging the potential for sustainable energy technology and policy in cities that too often lies untapped.

With global energy demand set to become even greater over the coming decades, *Energy Technology Perspectives 2016* (*ETP 2016*) looks at the technology and policy opportunities available for accelerating the transition to sustainable urban energy systems. Such potential could be the key to successfully driving an energy transition that many still think impossible, provided that local and national actions can be aligned to meet the sustainability objectives at both levels. Indeed, policies still have a long way to go in this regard: *ETP 2016* presents the annual IEA *Tracking Clean Energy Progress* report, which finds once again that despite some notable progress, the rate of needed improvements is far slower than required to meet energy sector sustainability goals.

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