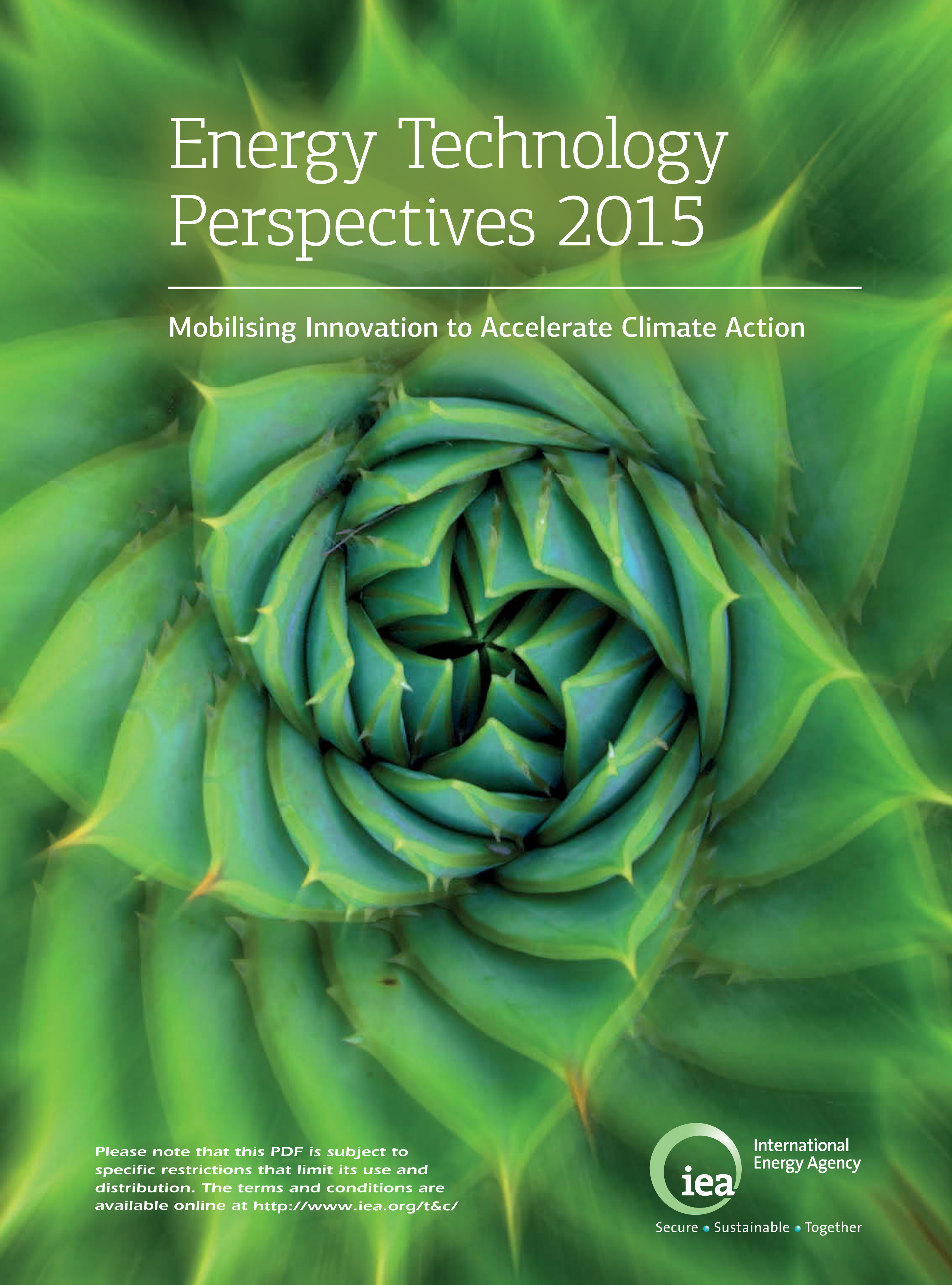

Energy Technology Perspectives 2015

Mobilising Innovation to Accelerate Climate Action

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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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Foreword

As the IEA looks to what is being heralded as a historic year for international cooperation on climate change mitigation, I wonder: will we be able to rise to the challenge? Drawing on the analysis of *Energy Technology Perspectives 2015* (*ETP 2015*) to survey today's energy landscape, I am as convinced as ever that the opportunities are there. Never has the promise of clean energy technology been so great. Yet, *ETP 2015* also highlights that never have the challenges surrounding deployment of the proper solutions been so daunting. We need to start thinking differently about what we can do to change the current sluggish pace towards sustainable change: we need to innovate!

ETP 2015 demonstrates that strategic action on clean energy technologies at national, regional and international levels has the capacity to move the world closer to shared goals for climate change mitigation while delivering benefits of enhanced energy security and sustainable economic development. Unfortunately, this report also shows that the current pace of action is falling short of the aim of limiting climate change to a global temperature rise of 2°C (in *ETP* modelling, the 2° Scenario or 2DS). Indeed, despite positive signs in many areas, for the first time since the IEA started monitoring clean energy progress, not one of the technology fields tracked is meeting its objectives. As a result, our ability to deliver a future in which temperatures rise modestly is at risk of being jeopardised, and the future that we are heading towards will be far more difficult unless we can take action now to radically change the global energy system.

ETP analysis shows that innovation needs strong support to be able to deliver on its promises. Indeed, inventions do not become innovations until they are deployed at scales sufficient to have an impact, and there are many non-technical barriers that can prevent very cost-effective solutions from playing their role. We must therefore adopt a systems perspective and recognise that technology innovation will only occur if the right policy signals and market and regulatory frameworks are in place to foster environments conducive to attracting the required levels of investments. International collaboration can provide the means to speed up innovation by sharing best practices and enabling a pooling of resources for solving common issues.

The theme of *ETP 2015*, "Mobilising Innovation to Accelerate Climate Action", not only reaffirms the need for government to stimulate energy technology innovation across production and consumption in all sectors, but also to recognise the impacts innovation can have on providing cost-effective means to achieve ambitious goals. This year's analysis highlights areas in which targeted action can deliver rapid impacts, for instance, by stimulating wider deployment of renewables such as wind and solar photovoltaics and by reducing emissions and improving efficiency in industry. It also demonstrates the importance of early action to enable longer-term benefits including the advancement of carbon capture and storage along the innovation pathway and boosting innovation capacity in emerging economies.

The timescale for this publication is 40 years. This also represents the IEA's history of supporting international technology co-operation through its energy technology network, which celebrates in 2015 four decades of progress in accelerating technology results through international collaboration. Through its broad range of energy technology initiatives, the

IEA enables countries, businesses, industries, and international as well as non-governmental organisations to share research on breakthrough technologies, to fill existing research gaps, to build pilot plants and to carry out deployment or demonstration programmes across the energy sector. This quiet success story demonstrates that, through a common shared vision, stakeholders worldwide can take actions that will enable the transformation needed to support energy security, economic growth, and environmental protection.

We need more collaboration of this type if we are to transcend the shortcomings of our current energy system, which is unsustainable and, therefore, insecure. The climate negotiations set to take place in Paris later this year make it imperative that the messages of *ETP 2015* be heard by all stakeholders and turned into ambitious pledges for actions. This is the time to construct a clean energy future that works for everyone, and for our leaders to have the wisdom to seize the power of innovation to benefit from the best that technology offers.

This publication is produced under my authority as Executive Director of the IEA.

Maria van der Hoeven
Executive Director
International Energy Agency

Executive Summary

Energy technology innovation is central to meeting climate mitigation goals while also supporting economic and energy security objectives. Ultimately, deploying proven, cost-effective technologies is what will make the energy system transformation possible. Continued dependence on fossil fuels and recent trends such as unexpected energy market fluctuations reinforce the role of governments, individually and collectively, to stimulate targeted action to ensure that resources are optimally aligned to accelerate progress. Establishing policy and market frameworks that support innovation and build investor confidence over the long term is a first-order task to deliver.

Energy decarbonisation is under way, but needs to be boosted

The year 2015 should mark a turning point in global climate change action. As leaders from around the world strive to reach agreement on the need to move quickly on multiple fronts, capturing the benefits of an energy transition should be a top priority. As the world prepares for assertive decisions at the UN Framework Convention on Climate Change (UNFCCC) negotiations, decision makers should focus on the wide range of benefits that can be delivered to society by transforming the energy system. International Energy Agency (IEA) analysis shows that it is realistic and economically sensible to pursue a clean energy agenda, and that tools and mechanisms exist to support innovative and transformative changes that lead to an affordable, secure and environmentally sustainable energy future. But recent trends reaffirm the need to accelerate energy technology innovation, including through policy support and new market frameworks.

Decoupling of energy use from gross domestic product (GDP) and population growth continues, but the current rate needs to double to achieve the 2°C Scenario (2DS). On the global level, the energy intensity of GDP and the carbon intensity of primary energy both have to be reduced by around 60% by 2050 compared with today. This implies that the annual rate of reduction in global energy intensity needs to more than double – from 1.1% per year today to 2.6% by 2050. Recent progress towards the 2DS is encouraging but remains insufficient; it is troubling that advances in those areas that were showing strong promise – such as electric vehicles and all but solar photovoltaics (PV) in renewable power technologies – are no longer on track to meet 2DS targets.

The unexpected decline in fossil fuel prices creates challenges and opportunities for decarbonising the energy system. While the recent drop in fossil fuel prices changes the short-term economic outlook of energy markets, using it to justify a delay in energy system transformation would be misguided in the long term. Short-term economic gains and delaying investment in clean energy technologies will be outweighed by longer-term costs. In fact, shifting to clean energy and achieving more efficient energy production and consumption can provide an energy security hedge against future market uncertainty. Deployment of innovative technologies that exploit clean domestic sources would reduce dependence on resources exposed to market price fluctuations.

Lower fossil fuel prices should also be considered as an opportunity to better align pricing with the true costs of energy production, in part by phasing out fossil fuel subsidies and introducing carbon pricing. Such an approach would substantially boost the perceived market viability of low-carbon technologies, driving investments in research, development, demonstration and deployment (RDD&D). In the case of carbon capture and storage (CCS), for example, lower fossil fuel prices reduce costs associated with the energy penalty inherent in adding CCS to energy generation or industrial processes. In turn, this reduces the level of support needed from governments to promote private investment in reducing the carbon impact of continued fossil fuel use in these sectors.

Among energy end uses, heating and cooling systems offer substantial potential for decarbonisation that so far has been largely untapped. Today, heating and cooling in buildings and industry accounts for approximately 40% of final energy consumption – a larger share than transportation (27%). With 70% of heating and cooling demand relying on fossil energy sources, these end uses are estimated to have been responsible for 30% of global carbon dioxide (CO_2) emissions in 2012. Broad application of energy efficiency and switching to low-carbon final energy carriers (including decarbonised electricity) can push the fossil share to below 50% by 2050 with renewables (including renewable electricity) covering more than 40% of heating and cooling needs. Direct and indirect CO_2 emissions linked to heating and cooling would fall by more than one-third by 2050.

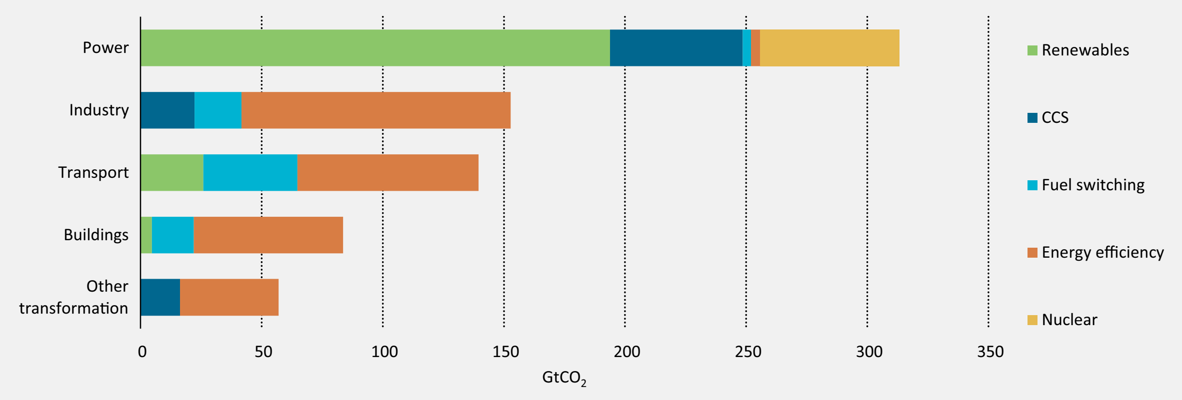
Decarbonising electricity supply and increasing electricity end-use efficiency remain two key components of the 2DS, as highlighted in *Energy Technology Perspectives 2014* (*ETP 2014*). With a share of 26% in total final energy consumption, electricity becomes the largest final energy carrier by 2050, slightly ahead of oil products. The biggest challenge by far lies in making a massive shift towards clean electricity production. Meeting the 2DS under such an increase requires reducing the global average carbon intensity of electricity production by more than 90%. Improving the efficiency of electricity use provides 12% of the cumulative emissions reduction, and also enables cost savings through reduced capacity and investment needs in the power sector. Electrified end-use options can also provide flexibility opportunities that support higher penetration of variable renewable electricity sources.

Accelerated uptake of low-carbon electricity supply options is needed to displace the continued deployment of new unabated fossil-based power plants. Utility-scale solar PV and onshore wind are now competitive with electricity generated by new conventional power plants in an increasing number of locations. While the cost gap between electricity from renewables and that from fossil fuels is narrowing, fossil plants still dominate recent capacity additions. Together with a slowdown in deployment rates of PV and wind, this undermines the trajectory needed to decarbonise energy supply and meet the 2DS renewable power targets. On a more positive note, the 2014 opening of the first commercial-scale coal-fired power plant with CO_2 capture marked a significant milestone for CCS, demonstrating that fossil fuels can be part of a sustainable energy system.

The promise of energy technology innovation can mobilise climate action

The energy sector accounts for around two-thirds of global CO_2 emissions in 2012, highlighting the benefits of innovation across a portfolio of clean energy technologies across all relevant sectors essential for decarbonisation. The technology mix that can deliver the emissions reduction will evolve over time as technologies move from research and development to market readiness. Support for technologies across all energy sectors provides the greatest potential to ensure uptake of immediately available solutions that keep climate goals achievable while also stimulating the initial development of more complex solutions needed for long-term deep decarbonisation. It also helps smooth the uncertainty inherent in individual technology development and increases the opportunity to align climate change mitigation goals with other energy policy objectives**.**

Figure I.1 Cumulative CO_2 reductions by sector and technology in the 2DS to 2050



Key point *A portfolio of low-carbon technologies is needed to reach the 2DS; some solutions will be broadly applicable, while others will need to target specific sectors.*

Wind and solar PV have the potential to provide 22% of annual electricity sector emissions reduction in 2050 under the 2DS; to fully exploit the performance improvements achieved through technology innovation over the past two decades, innovation is now needed at the system level. Experience shows that the main challenges to deployment – and thus the requirements that framework conditions need to meet – change as these technologies progress along the deployment curve. Thanks to innovations that improved their efficiency and reliability, onshore wind and solar PV are ready to be mainstreamed in many energy systems. Efforts to move in this direction should draw on the wealth of experience gained as various countries have passed through the earlier stages of inception and scale-up. Continued technology innovation will need to expand beyond wind and PV systems to encompass enabling technologies that reduce the variability of wind and solar PV or increase the flexibility of power systems. For very high deployment levels of wind and PV, innovation is needed in demand-side integration, energy storage and smart grid infrastructure. Widespread deployment of wind and PV technologies, consistent with the 2DS, now requires an integrated and well-designed policy and market regulatory framework.

The ability of CCS to enable fossil resources use while still contributing to CO_2 emissions reduction goals requires governments to shape markets that stimulate private investment in CCS and provide vital early commercial experience. Measures that raise the costs and risks of using fossil fuels without CCS, such as carbon pricing or emissions standards, will play important roles. But more targeted, market-based instruments are also needed to manage the investment risks and market failures in early stages of technology scale-up. This includes activities to develop CO_2 storage resources as national, regional or private assets. Given the importance of CCS for emissions reduction in industrial sectors and for enabling CO_2 removal options, the value of CCS – which will rise over time – needs to be appropriately rewarded. Governments can also leverage the political value of CCS to avoid early retirement of fossil-based generation plants and manage the pace of capital turnover, maintain diversified fuel sources and prices, and create jobs in low-carbon manufacturing.

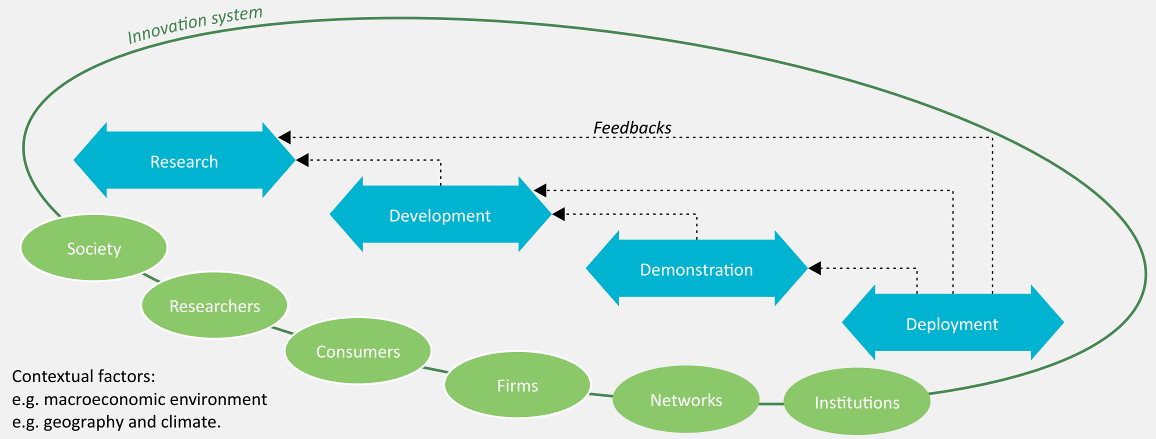
Aligning innovation goals on a global basis will enable the industry sector to reap the benefits of meeting the multifaceted challenge of decarbonisation. Almost 30% of direct industrial CO_2 emissions reduction in 2050 in the 2DS hinges on processes that are in development or demonstration today. In the medium term, the most effective measures for reducing industrial emissions include implementing best available technologies and energy efficiency measures, switching to low-carbon fuel mixes, and recycling materials. Deploying innovative, sustainable processes will be crucial in the long run, with CCS playing a key role. Integrating carbon capture, improving resource efficiency, reusing waste process streams and identifying alternative applications for diversified products should be cross-sectoral goals. To ensure the timely roll-out of innovative industrial processes, governments should seek to address barriers that are preventing progress such as economic and policy uncertainty, inadequate risk management, unbalanced collaboration and knowledge protection. Lack of clarity on when climate policies might make low-carbon production globally competitive, coupled with volatile energy prices, makes it difficult for industry to justify investments in low-carbon technologies and sustainable products.

Innovation support is crucial across the low-carbon technology spectrum

Both incremental and radical innovations are needed to decarbonise the global energy system; government support across all phases of RDD&D can facilitate both. Governments can play a critical role for promising technologies by ensuring stable, long-term support in all stages of innovation – i.e. from basic and applied research through to development, demonstration and deployment phases. An interactive and iterative innovation process, involving multiple stakeholders, captures feedback at various steps to support both "learning by research" and "learning by doing". Learning to date emphasises the need to support technology innovation with strategically aligned policy and market frameworks that reflect the level of technology maturity.

Understanding which of the available policy tools are effective for different technologies – and at different stages of their maturity – is key to success. Allocation of resources towards different technologies must consider both short- and long-term opportunities and challenges for innovation. Market-ready (or near market-ready) solutions, including many energy efficiency technologies and several renewable energy technologies, can deliver emissions reduction in the short term. At this stage, the responsibility of policy makers is to ensure efficient use of support resources (which are often scarce), prioritising support for the most promising technologies while still maintaining a portfolio of solutions. Ongoing RDD&D support is needed for technologies that show long-term potential but still require efforts to reduce costs, carry out large-scale demonstrations or achieve performance improvements for market entry.

Figure I.2 Systems-based interactive innovation



Sources: GEA (2012), *Global Energy Assessment: Toward a Sustainable Future*, Cambridge University Press, Cambridge, United Kingdom and New York; the International Institute for Applied Systems Analysis, Laxenburg, Austria.

Key point *Interactions across the entire innovation system will enable actors to develop necessary incremental improvements and breakthroughs in technologies needed to meet climate goals.*

The challenges associated with deployment warrant special attention: successful development and demonstration do not guarantee commercial success of a given technology. The innovation path exposes technologies to many challenges, breeding both successes and failures. Experience shows that even when low-carbon technologies prove cost-effective under prevailing market conditions, other (non-cost) barriers can stall their uptake and limit private sector engagement. Instruments such as minimum efficiency standards and information campaigns (designed to address risk aversion to new technologies or promote behavioural change) can help to create the favourable market environment needed to make the leap to large-scale deployment. New policies or regulatory approaches (e.g. standards and codes for buildings or vehicles or market rules in power systems) and public-private cross-sectoral frameworks along industrial product value chains are also needed. Creative approaches, such as capturing and valuing the multiple benefits of technology innovation, leveraging research on consumer behaviour, and bundling policy packages to address multiple barriers can also boost deployment.

Achieving widespread deployment of the needed technologies in the pipeline requires strategic, parallel action in technology development and market creation to close the cost gap inherent in their application. For example, CCS deployment has begun in specific regions and sectors where policies are well-aligned with strategic local and commercial interests. Meeting industrial demand for CO_2, such as in enhanced oil recovery operations, is one non-climate benefit that is driving CCS technological development and reducing the cost gap. Other important drivers that support early deployment include climate policy and public investment in innovation. Research and development (R&D) alone will not deliver the necessary performance improvements and cost reductions, however;

it must be leveraged through learning by doing in demonstration and deployment efforts, which can benefit from non-climate drivers for early stage projects.

Multi-stakeholder co-operation in support of international climate initiatives can greatly accelerate low-carbon technology innovation in alignment with global climate goals. Ambitious goals set within the framework of initiatives such as the UNFCCC can create consensus on shared objectives and build confidence in ongoing development of both established technologies and emerging low-carbon solutions. As the 2015 UNFCCC agreement is expected to be based on nationally determined climate goals, an important element is to provide signals that support scale-up of technology innovation to put the world on a 2DS trajectory. To build greater confidence in the feasibility and increase ambition of mitigation goals, the agreement could also strengthen mechanisms to inform parties on technology innovation trends. In general, multilateral collaboration on energy technology innovation could provide greater confidence that international aggregate action is aligned with global climate goals.

Innovation in emerging economies could deliver greatest, fastest advances towards climate change goals

Growing demand for energy – and the infrastructure needed to provide it – creates a unique opportunity for emerging economies to reduce CO_2 emissions by deploying low-carbon technologies. Energy demand growth, linked to increasing global population, economic development and the objective of achieving universal energy access, is a major driver for energy system expansion. During infrastructure build-out, emerging economies can be early movers in applying a systems approach to the roll-out of advanced low-carbon technologies. For example, “dynamic” power systems – that is, systems characterised by high growth rates in demand and/or facing significant investment requirements – may offer better opportunity to balance supply and demand in more efficient ways, in contrast to more “stable” systems where the transition puts incumbent generators under high levels of economic stress. Planning and building dynamic systems taking into account variable renewable energy targets would avoid the need for costly retrofits at later stages.

Non-member economies of the Organisation for Economic Co-operation and Development (OECD) are particularly important to long-term decarbonisation of the global industrial sector. As material demand rises along with their share of global markets, these economies hold significant potential to deploy new, low-carbon industrial processes. Ultimately, their uptake of innovative processes accounts for almost three-quarters of worldwide direct industrial CO_2 emissions reduction in 2050 in the 2DS. Two key prerequisites are needed to realise this potential: first, international co-operation to support technology and knowledge transfer, as well as the buildup of domestic skills and capacity for innovation, and second, the establishment of market environments that are conducive to commercially viable and innovative energy technologies.

While both OECD countries and OECD non-members will need to alter their energy systems, innovation pathways, as well as policy and market frameworks, will vary across regions. Decisions about the appropriate mix of technology solutions will have to take into account specific circumstances at national and regional levels (Figure I.3). Open and transparent communication among stakeholders can support the adoption of solutions most suited to local needs, thereby securing early buy-in and long-term sustainability of the transition. Multilateral collaboration can help identify commonalities or differences in local circumstances and challenges, and increase the relevance of shared lessons learned and best practices.

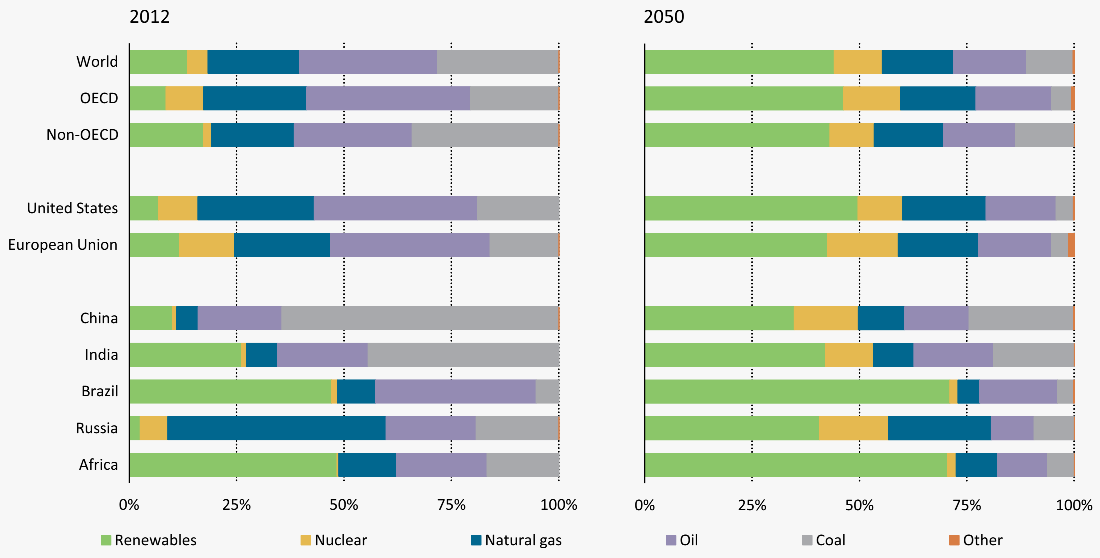
Box I.1 The importance of international collaboration

Understanding circumstances in various regions of the world allows better-informed decisions on which solutions could be best suited to local requirements (see Figure I.3). International dialogue can help share best practices and provide insights in decision rationales that can effectively support domestic transition plans.

Since its inception, the IEA has been actively engaged in multi-lateral energy technology collaboration to support the development and deployment of clean energy technologies through its core institutional activities. Among them:

- the Energy Technology Initiatives, enabling innovation through 39 co-operative agreements involving more than 6000 experts from over 50 countries that work together to accelerate advances in energy technologies
- the whole range of IEA publications, which analyses the wealth of information provided by IEA multilateral energy technology initiatives to inform more effective decision-making. Notably, IEA Technology Roadmaps allow stakeholders to agree on the necessary milestones to achieve the sustainable energy transition
- the International Low-Carbon Technology Platform, which is the chief IEA tool for multilateral engagement on clean technologies between its member and partner countries, the business community and international organisations
- training and capacity-building activities to spread best practices in energy policy and energy statistics.

Figure I.3 Regional primary energy demand profiles in the 2DS



Key point *Different national circumstances, including availability of resources, will require tailor-made solutions and pathways for deep decarbonisation by 2050 that initially leverage available solutions before developing home-grown solutions.*

Domestic innovation of low-carbon technologies in emerging economies is increasing, an important complement to their current reliance on absorbing and/or adapting technologies developed elsewhere. The People's Republic of China (hereafter "China"), India and Brazil (among other countries where a vibrant manufacturing sector underpins innovation) are advancing deployment of a number of low-carbon technologies. But the status of innovation across a broader range of emerging economies is mixed. Their overall share of global research, development and demonstration (RD&D) is rising and some countries (particularly China) are closing the gap in key areas, but patent data indicate that innovation remains concentrated in a few OECD countries. A strong domestic market, coupled with industrial capacity and an export-oriented economy, are important factors for developing and deploying more innovative technologies and systems improvements. At the regional level, growing innovation capacity and technology transfer, along with increasing investment flows, both within and among emerging economies are creating new reciprocal opportunities.

An important role for OECD countries is to engage actively in low-carbon initiatives in emerging economies; sharing lessons learned to accelerate their progress along the innovation pathway will be mutually beneficial and support global climate goals. Recognising that actions in emerging economies will play a vital role in achieving global emissions reduction targets, OECD countries can both support actions in emerging economies and design their own RDD&D strategies to address the needs of emerging economies. This approach would benefit both the supplier and recipient of technologies, while contributing to decarbonisation of global energy systems. Policy and market experience acquired in OECD countries may be beneficial as emerging economies seek to strengthen their innovation systems, particularly in the areas of allocation and management of RD&D funds or effective system and policy architecture for deploying renewable energy across key regions.

Box I.2

ETP 2015 country case study: Energy technology innovation in China

To achieve its aim of being a global leader in low-carbon technology markets, China will need to further strengthen its ability to innovate. Over the past decade, China has used its energy and science and technology policies to advance technology development and deployment in closer alignment with economic and climate objectives.

China has demonstrated its capacity to deliver original, integrated and optimised innovation. Continued success will increasingly rely on joining and expanding international innovation networks and harnessing their power to collaboratively transform domestic and global energy systems. As China continues to move up the value chain in advanced technology and innovative systems, challenges and opportunities inherent in the global technology transfer landscape will affect both the import and export of Chinese technologies.

Recent adoption of more stringent air pollution and environmental policies in China, along with measures to improve coal quality and the efficiency of coal-fired electricity generation, provide additional incentives for clean energy innovation. Through these energy policy and technology reforms, China seeks to capture opportunities for economic advantage from the transition to a cleaner, more sustainable and increasingly market-oriented system.

Ultimately, the increasing capacity of Chinese industry to accelerate innovation in low-carbon technologies can boost the confidence of policy makers to pursue even more ambitious climate mitigation goals, knowing they can be achieved with positive trade-offs for energy security and economic development.

Current RDD&D investment falls short of long-term climate goals, misses opportunity for dividends

Substantial financial resources are needed to achieve the energy transformation: public financing models and RD&D funds need to be mobilised to leverage private-sector capital in new ways. Public expenditures on energy RD&D have been growing in absolute terms since the late 1990s; their share of total R&D, however, has fallen dramatically from a peak of 11% in 1981 and has remained flat between 3% and 4% since 2000. Governments alone will not be able to deliver the clean energy investment consistent with the 2DS objectives; unlocking private-sector capital is essential. To leverage and direct private-sector capital flows, governments need to implement policy tools that will help address investor concerns about the inherent high financial and policy risks associated with large energy investments.

Examples of effective action exist in OECD countries, with some models being adopted or developed in emerging economy contexts. Specifically, China and Brazil have used subsidised, low-cost debt to finance low-carbon technologies in domestic markets, with creative models for venture capital, private equity and state-owned enterprise financing. China and Brazil have taken the lead in using national development banks for climate financing in developing countries; India and other countries are considering similar opportunities and seeking ways to foster South-South transfers of technology, skills and knowledge. But proper governance structures remain essential to reduce risks to investors and decrease the cost of capital in emerging economies.

Economic analysis shows that fuel cost savings more than offset the additional investment costs of the 2DS, creating a compelling case for investing in the transition to a low-carbon global energy system. About USD 40 trillion additional investment (relative to the USD 318 trillion expected to be invested anyway in the business-as-usual 6°C Scenario [6DS]) is needed to transition to a global low-carbon energy system in the 2DS. This represents less than 1% of the cumulative global GDP over the period from 2016-50 and sets the stage for fuel cost savings of USD 115 trillion – i.e. almost triple the additional investment.

Setting long-term technology goals – and tracking progress towards them – can build the confidence needed to mobilise private investment in RDD&D. The effectiveness of efforts to stimulate RDD&D should be demonstrated, particularly on the part of policy makers who are accountable for appropriate use of resources. Collective efforts should be taken to identify short- and long-term technology needs at the global level, and to develop tools to track progress in technology development against defined benchmarks. Technology benchmarks can be based on indicators such as technical performance (e.g. efficiency or capacity factor), capital cost, cost of energy generated, life cycle assessments, etc. Ongoing evaluation of innovation efforts is needed to assess success, accumulate learning experiences and determine how to best support specific technologies. The ability to assess the potential of low-carbon technologies and track progress towards larger goals through a rich set of metrics is essential to ensure that policies implemented are effectively aligned and deliver on stated objectives. Such a process would need built-in flexibility to account for faster or slower progress, as well as the influence of external conditions (e.g. energy prices or macroeconomic conditions).

Multilateral collaboration can improve the cost-effectiveness of energy technology innovation and build confidence that progress is being achieved at global scale. Globalisation of the economy is sparking a move towards more open innovation frameworks that help pool resources to accelerate R&D, underwrite demonstration and stimulate faster deployment of proven technologies. Multilateral initiatives have grown significantly since 2005, covering areas such as technology and knowledge transfer, regulatory and market analysis, and policy dialogue and co-ordination. These initiatives increase the capacity of local innovation and successful deployment of innovative energy technologies (in the context of local policies and environments) to cumulatively contribute to global climate change mitigation efforts.

Box I.3 Recommendations to energy ministers

Each chapter of *ETP 2015* provides policy recommendations specific to individual sectors or challenge areas. Five high-level recommendations emerge to set the stage for a low-carbon future:

Governments should develop a vision for a clean energy future, especially in the context of the 2015 UNFCCC climate agreement. Sector- and technology-specific actions and targets should be identified to accelerate the decarbonisation of the energy sector. Governments should ensure that support continues beyond technology development to address policy and market barriers.

National policy-makers should enact stable policies to ease access to finance by reducing the risks for investors. Financing costs for low-carbon technologies can be a major hurdle for projects. Policy frameworks that support new business models (such as energy contracting or green bonds) can help attract investors to areas that face financing challenges.

International negotiators should base future emissions reduction ambitions on a vision that includes the expected progress on clean energy technologies. Governments should give full consideration to future technologies that will be deployed through continued innovation, as well as to the anticipated improved performance and reduced costs of today's best available technologies.

Private and public support should be measurable and should target all phases of RDD&D to facilitate both incremental and radical innovation. Technology-specific indicators to track progress on development and deployment should be complemented by sector-specific metrics in the power, buildings, industry and transport sectors.

OECD countries should support actions in emerging economies and design their own RDD&D strategies to address the needs of emerging economies. This approach would benefit both suppliers and recipients of technologies while contributing to decarbonisation of global energy systems.

Acknowledgements

This publication was prepared by the International Energy Agency's Directorate of Sustainable Energy Policy and Technology, under the leadership of Didier Houssin, and in co-operation with other divisions of the IEA. Jean-François Gagné, Head of the Energy Technology Policy Division developed the concept for this edition and offered invaluable support, guidance and input throughout the process.

David Elzinga was the lead author and Project Manager and had overall responsibility for the design and implementation of the study.

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The Tracking Clean Energy Progress (TCEP) chapter was led by Emer Dennehy, Davide D'Ambrosio and Cecilia Tam. In addition to *ETP 2015* main authors, TCEP topical authors were Yasmina Abdelilah, Heymi Bahar, Anselm Eisentraut, Costanza Jacazio, Alexander Koerner, Tristan Stanley, Tali Trigg and external author Henri Paillère (OECD Nuclear Energy Agency).

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Marilyn Smith (consultant) held the role of Managing Editor with the support of external editors Erin Crum and Andrew Johnston.

The IEA Data Centre led by Duncan Millard provided support for data and analysis, including Jean-Yves Garnier (former Head of the IEA Energy Data Centre), Zakia Adam, Pierre Boileau, Aidan Kennedy, Taejin Park and Roberta Quadrelli.

The IEA Communication and Information Office led by Rebecca Gaghen, and including Jane Barbière, Muriel Custodio, Astrid Dumond, Charlotte Forbes, Greg Frost, Angela Gosmann, Christopher Gully, Kevin Nellies, Bertrand Sadin, Magdalena Sanocka, Kathleen Sullivan, Therese Walsh and Robert Youngblood guided production and communication activities.

The Office of the Legal Counsel, led by Pascal Laffont and including Rachael Boyd, Rachel Briggs, Eleonor Grammatikas, Bérengère Merlo and Elizabeth Spong, provided legal support over the course of the project.

The work was guided by the members of the IEA Committee on Energy Research and Technology (CERT) who helped to substantially improve the policy relevance of this document. The technology analysis in this book draws extensively upon the unique IEA international network for collaboration on energy technology. Numerous experts from many of the IEA Implementing Agreements have contributed with data, suggestions and expert reviews.

The Standing-Group on Long-Term Co-operation (SLT), the Working Party on End-Use (EUWP), the Working Party on Fossil Fuels (WPFF), the Working Party on Renewable Energy (REWP) and the Experts' Group on R&D Priority Setting and Evaluation (EGRD) also provided helpful inputs and suggestions.

This study would not have been possible without the generous voluntary contributions and in-kind support from many IEA governments, including Canada (Natural Resources Canada), France (Ministère de l'Écologie, du Développement durable et de l'Énergie), Japan (Ministry of Economy, Trade and Industry), Switzerland (Swiss Federal Office of Energy), Sweden (Ministry of Energy and Environment), the United Kingdom (Department of Energy & Climate Change) and the United States (Department of Energy). Exceptional support was also given by the Japan Gas Association.

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A large number of reviewers provided valuable feedback and input to the analysis presented in this book (in alphabetic order):

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Choongsik Bae (Combustion Implementing Agreement), Sangjoo Baek (Korea Institute of Energy Technology, Evaluation and Planning), Michael Balfe (ALSTOM Carbon Capture), Kimberly Ballou (US-DOE), Richard Baron (OECD), David Baxter (European Commission JRC/IEA Bioenergy Task 37), Chris Bayliss (International Aluminium Institute), Alexis Bazzanella (Dechema), Thore Berntsson (Industrial Energy Technology Systems Implementing Agreement), Jean-Pierre Birat (European Steel Technology Platform), Christer Bjórkqvist (European Turbine Network), Markus Blesl (IER, University Stuttgart), Dr Eduard Bolshakov (ALITinform), George Booras (EPRI), Dan Brady (Natural Resources Canada), Mick Buffier (Glencore), Dubravka Bulut (Natural Resources Canada), Carol Burelle (Natural Resources Canada), Dan Burt (Suncor), Karl Buttiens (ArcelorMittal), Marie Bysveen (SINTEF).

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The individuals and organisations that contributed to this study are not responsible for any opinions or judgements contained in this study. Any errors and omissions are solely the responsibility of the IEA.

Workshops

A number of workshops and meetings were held in the framework of this study and during the development of technology roadmaps. The international experts participating in these workshops were able to provide valuable new insights, data and feedback for this analysis. The workshops covered various highly relevant areas, including:

- Gaps and Strategic Opportunities for International Collaboration on Low-carbon Energy Technologies: 27 February 2014, Paris.
- Modelling and Analyses in R&D Priority-Setting and Innovation: 23-24 April 2014, Paris.
- IEA Working Party on Renewable Energy Technologies (REWP) Workshop on Renewables and Energy Systems Integration: 8-9 September 2014, Golden, Colorado.
- Potential for Innovation in CO_2 Capture Technology: 7 October 2014, Austin, Texas.
- Workshop of the Technology Executive Committee: Strengthening national systems of innovation in developing countries: 13-14 October 2014, Bonn.
- IEA Global Industry Experts Dialogue Workshop: 23 October 2014, Paris.

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Part 1

Setting the Scene

The International Energy Agency (IEA) vision for a sustainable energy system is set out in Part 1 of *Energy Technology Perspectives* (*ETP*) *2015*, along with the policies, technologies and financial investments needed to achieve it. Recent events, global energy trends and the three main *ETP* scenarios are covered in Chapter 1, with analysis across the entire energy sector. Technology-rich modelling of these scenarios to 2050 reveals the possible pathways to a sustainable energy future in which appropriate policy support and technology choices are driven by economics, energy security and environmental factors.

Against the backdrop of the urgent need to transform the way energy is supplied and used, Chapter 2 assesses recent progress on clean energy and serves as the fifth IEA submission to the Clean Energy Ministerial. Offering high-level insights into recent success stories – as well as evident cases of sub-optimal deployment – across demand and supply sectors, it serves to promote uptake of proven technologies while also acting as a call to action for more effective support from policy makers where needed.

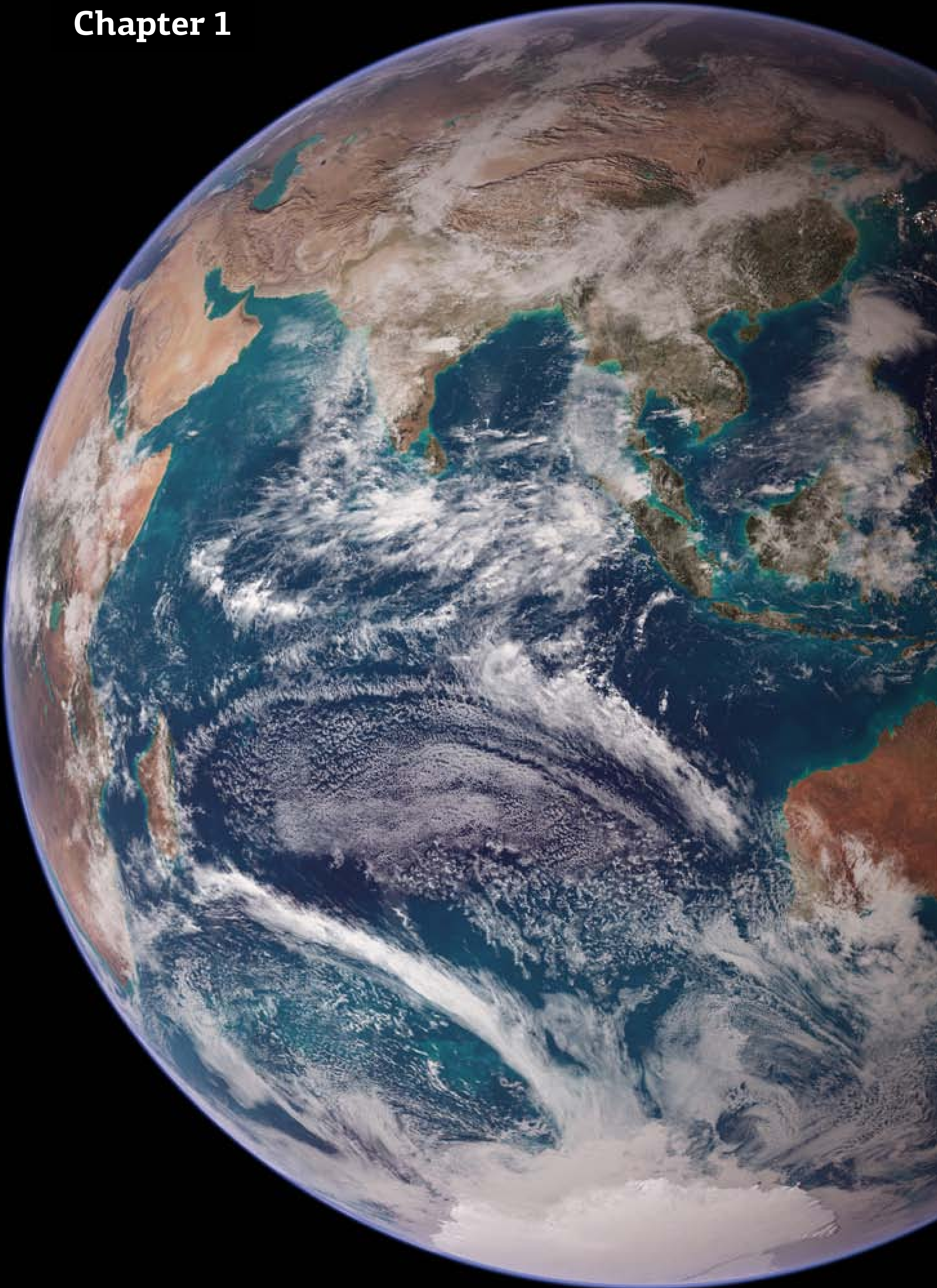
Chapter 1 **The Global Outlook** **27**

Decoupling economic growth from energy demand and associated emissions through energy efficiency and decarbonisation of supply are key elements to sustainably meeting long-term energy system goals. Decarbonising electricity supply remains vital, but stepping up action to achieve low-carbon heating and cooling as well as cleaner transportation systems is also central. Decarbonising the global energy system has a strong economic rationale, as the long-term economic benefits of a low-carbon transition greatly outweigh the initial costs of achieving it.

Chapter 2 **Tracking Clean Energy Progress** **71**

Progress is continuing in the deployment of clean energy technologies. Solar photovoltaics and wind are increasingly competitive in favourable locations. The bid to decarbonise fossil fuel use achieved a major milestone in 2014 with the opening of the world’s first power plant to be equipped with carbon capture and storage technologies. Deployment rates of low-carbon technologies, however, have plateaued in all regions while unabated coal-fired capacity continues to be expanded; such trends jeopardise the feasibility of meeting long-term climate goals. Actions by governments and industry have fallen short of stated ambitions, and should be stepped up to avoid escalating future costs of decarbonisation.

Chapter 1



The Global Outlook

The transition to a low-carbon energy system is achievable, but requires rapid action to drastically alter recent trends. Reducing energy consumption through energy efficiency and decarbonising the remaining demand are the key elements to success. Decarbonising the electricity supply remains vital, but it's time to stop neglecting heating, cooling and transport systems.

Key findings

- ***The energy intensity of global gross domestic product (GDP) and the carbon intensity of primary energy both have to be reduced by around 60% by 2050 in the 2°C Scenario (2DS) on a global level compared with today.*** *Some progress has been made in decoupling energy use and GDP but the rate needs to be accelerated, from 1.1% per year over the last decade to 2.6% by 2050. No progress has been observed in decarbonising primary energy, though its carbon intensity needs to be reduced by 2.7% per year by 2050 in the 2DS.*
- ***Action across all supply and demand sectors is needed to change these trends,*** *with the power sector providing around 40% of the cumulative emissions reduction to achieve the 2DS (compared with the 6°C Scenario [6DS]), followed by transport and industry (with reductions of around 20% each), buildings (12%), and other transformation (8%).*
- ***Energy efficiency is crucial to reduce dependency on fossil fuels, accounting for almost 40% of the cumulative emissions reduction needed to achieve the 2DS (relative to the 6DS).*** *Widespread energy efficiency measures in the 2DS could reduce annual demand by 126 exajoules (EJ) in 2050, an amount representing 28% of the global final demand in 2050 in the 2DS and being comparable to the current final energy consumption of China and the European Union combined.*
- ***Industry was responsible for almost 40% of global carbon dioxide (CO_2) emissions in 2012, followed by buildings (29%) and transport (26%).*** *These figures include upstream or indirect emissions for the production of electricity and oil products, which are consumed by the end-use sectors. Indirect emissions, mainly from electricity generation, account for almost half of industry emissions on a global level and more than 70% in the case of buildings.*
- ***Improving the efficiency of electricity use is therefore key; electricity savings provide 12% of the cumulative emissions reduction to reach the 2DS.*** *These electricity savings not only translate on the generation side into reduced fuel use and emissions, but often result also in cost savings through reduced capacity and investment needs in the power sector.*
- ***Improved electricity efficiency in combination with decarbonisation supports increase electrification in end-use sectors.*** *Global growth in final electricity demand by 2050 is three times higher than the growth in total final energy demand; electricity becomes the largest final energy carrier, ahead of oil products, with a share of 26% in total final energy consumption.*

- ***Heating and cooling in buildings and industry today are estimated to accounts for more than 40% of final energy consumption,*** *a larger share than transportation with 27%. Heating and cooling applications have been approximately responsible for 30% of global CO_2 emissions in 2012.*
- ***Direct and indirect CO_2 emissions linked to heating and cooling can be reduced by 50% by 2050 in the 2DS through energy efficiency and by switching to low-carbon final energy carriers.*** *Today, 70% of final energy consumption for heating and cooling is based on fossil energy sources; in the 2DS, this share falls below 50% by 2050 with renewables, including renewable electricity, covering more than 40% of heating and cooling needs.*
- ***Efficient vehicles, alternative fuels and instruments that better manage travel patterns with shifts toward more efficient modes are crucial for emissions reduction in the transport sector.*** *Fuel economy standards deliver the largest savings in the short term. In the longer term, policy action has to encourage mass deployment of more innovative technologies, such as electric vehicles (EVs), plug-in hybrids (PHEVs) and fuel-cell electric vehicles (FCEVs), as well as low-carbon fuels.*
- ***Reaching the 2DS requires additional investments of around USD 40 trillion between today and 2050.*** *This represents 13% of the investments in the 6DS, but is more than offset by cost savings of around USD 115 trillion through dramatically less consumption of fossil fuels.*

Opportunities for policy action

- *Energy efficiency plays a central role in achieving the transition to a 2DS, by reducing fossil energy use and emissions in the near term. The development and deployment of low-carbon technologies and fuels (such as renewables, nuclear, and carbon capture and storage [CCS]) are particularly important for the long-term decarbonisation of the energy system.*
- *Governments should develop a vision for a clean energy future, including long-term goals and stable policy frameworks. Carbon pricing and removing fossil fuel subsidies are important to ensure that prices reflect the true costs of energy. Price on its own, however, will not deliver the 2DS objectives; a wide range of policy instruments (e.g. standards and codes for buildings or vehicles) are needed to address other barriers not influenced by price.*
- *Financing costs for low-carbon technologies can be a major hurdle for projects. Stable policies should aim to ease access to finance by minimising the risks for investors. Policy frameworks that support new business models (such as energy contracting or green bonds) may help attract investors to areas that face financing challenges (such as energy efficiency).*
- *Heating and cooling needs, and their implication for energy use and CO_2 emissions, are often overlooked in policy action. Being linked to different parts of the energy system and having vastly different uses in buildings and industry, heating and cooling involve different policy areas including fuel taxation, building regulation and urban planning. Integrated policy approaches are important to take into account and address these interdependencies.*
- *Waste heat recovery from power plants and industrial production processes is a nascent area that shows strong potential to provide part of heating and cooling demand in the future, especially in emerging economies. Holistic policy and integrated planning approaches are needed to better understand the potential and the costs.*
- *Sufficient and consistent government and private sector support of technology innovation is essential to meet long-term climate security and economic goals in the energy system. Technological advances and innovation are embedded in the modelling work that underpins* Energy Technology Perspectives (ETP). *In this modelling, technology costs decline with increasing deployment, following anticipated experience curves (see Part 2 of* ETP 2015*).*

Global energy-related CO_2 emissions continue to rise, having reached a new all-time high of 31.7 gigatonnes (Gt) in 2012.[1, 2] Despite this discouraging trend in the short term, substantial policy initiatives may be changing the tide. In November 2014, China and the United States, the two largest CO_2-emitting countries, announced a joint initiative to curb CO_2 emissions and promote clean energy by 2030. Earlier in 2014, the European Union confirmed its aggressive greenhouse gas (GHG) mitigation ambitions by agreeing on a 40% reduction target by 2030 compared with 1990 levels. These agreements boost optimism for the climate negotiations at the upcoming United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP) in Paris in December 2015.

Against the background of these recent developments, this Global Outlook provides an overview of the current status of the global energy system and outlines changes needed to achieve the transition to the agreed target of limiting global temperature rise to 2°C. As in past editions of *ETP*, it does so by using three scenarios (Box 1.1).

- **The 6DS** assumes no GHG mitigation efforts beyond policy measures already implemented, which could lead to a 60% increase in annual energy- and process-related CO_2 emissions to a level of 56 gigatonnes of CO_2 ($GtCO_2$) and a potentially devastating global average long-term temperature increase of around 5.5°C.
- **The 4°C Scenario (4DS)** takes into account climate and energy policies being planned or under discussion, and projects an annual emissions level of 41 $GtCO_2$ with a less dramatic temperature increase of 3.7°C.
- **The 2DS** puts forward a pathway that gives at least a 50% chance to limit mean temperature increase below 2°C, reaching an annual emissions level of 14 $GtCO_2$ by 2050 – i.e. almost 60% below current levels. Even this is not the end point, however; as shown in the scenario analyses of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report, mitigation efforts must be continued beyond 2050 under a 2°C pathway to attain net zero emissions in the second half of the century (IPCC, 2014).

Past experience warrants caution regarding the encouraging policy announcements mentioned above. The Energy Sector Carbon Intensity Index (ESCII) shows that policy action over the past two decades has not yet delivered significant changes in the average global CO_2 intensity of primary energy use (Figure 1.1). Although reductions are evident in member countries of the Organisation for Economic Co-operation and Development (OECD), the 2DS intensity targets for 2050 show the steep decline needed over the next four decades, in both OECD and OECD non-member economies.

While CO_2 mitigation strategies for energy supply (especially for the power sector) garner a great deal of attention, they are only one part of the sustainable energy system solution. Decoupling energy demand from economic growth through improvements in energy efficiency is another important stream of action. Energy efficiency in end-use sectors is in many cases an option that can be implemented in the near term, thus providing time to further develop technologies and transform the energy system for the longer term, deep emissions reduction paths. In the scenarios presentation, this Global Outlook emphasises the role energy efficiency can play on the demand side – i.e. in the major end-use sectors and in regions where economic development and energy demand are projected to grow most rapidly.

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[1] These figures exclude process emissions in industry. If not explicitly stated otherwise, CO_2 emissions in the *ETP* analysis include both, energy- and process-related CO_2 emissions.

[2] The year 2012 is used as base year for the scenario analysis, as it represents the latest year for which comprehensive energy and CO_2 balances are available on a global scale.

Box 1.1 Scenarios in *ETP 2015*

The *ETP* scenario analysis is based on four interlinked technology-rich models for the energy supply, buildings, industry and transport sectors. Depending on the sector, this modelling framework covers 28 to 39 world regions or countries, over the time horizon from 2012 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 back-casting to develop plausible pathways for a desired long-term outcome. The *ETP* scenarios should not be considered as predictions of what is going to happen, rather, they explore the impacts and trade-offs of different technology and policy choices, thereby providing a quantitative approach to support decision making in the energy sector. While different, the *ETP* scenarios are complementary to those explored in the IEA *World Energy Outlook* (*WEO*).

The **6DS** is largely an extension of current trends. By 2050, primary energy use grows by almost two-thirds (compared with 2012) and total GHG emissions rise even more. In the absence of efforts to stabilise atmospheric concentration of GHGs, average global temperature rise above pre-industrial levels is projected to reach almost 5.5°C in the long term (by 2050) and almost 4°C by the end of this century. Already, a 4°C increase within this century is likely to stimulate severe impacts, such as sea level rise, reduced crop yields, stressed water resources or disease outbreaks in new areas (World Bank Group, 2014). The 6DS is broadly consistent with the *WEO* Current Policy Scenario through 2040.

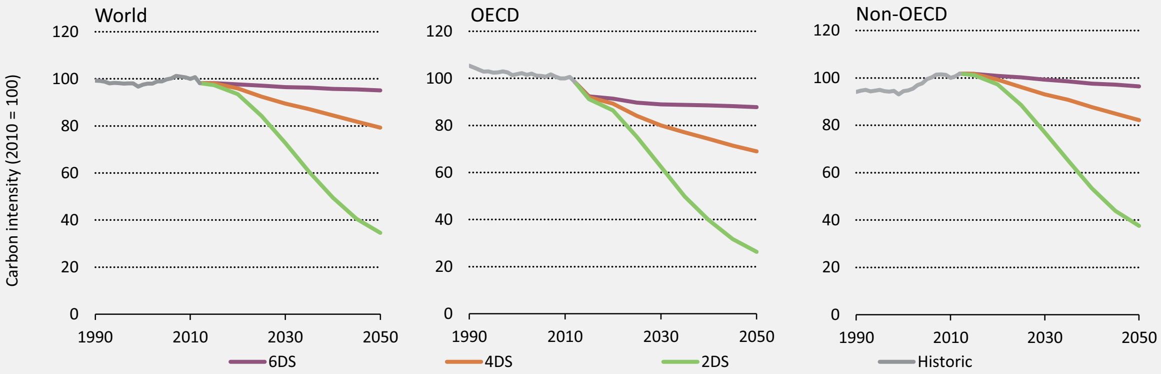
The **4DS** takes into account recent pledges made by countries to limit emissions and step up efforts to improve energy efficiency, which helps limit long-term temperature rise to 4°C (by 2050). The 4DS is, in many respects, already an ambitious scenario that requires significant changes in policy and technologies compared with the 6DS. This long-term target also requires significant additional cuts in emissions in the period after 2050, yet with average temperature likely to rise by almost 3°C by 2100, it still carries the significant hazard of bringing forth drastic climate impacts. The 4DS is broadly consistent with the *WEO* New Policies Scenario.

The **2DS** is the main focus of *ETP 2015*. It lays out the pathway to deploy an energy system and emissions trajectory consistent with what recent climate science research indicates would give at least a 50% chance of limiting average global temperature increase to 2°C. The 2DS sets the target of cutting energy- and process-related CO_2 emissions by almost 60% by 2050 (compared with 2012) and ensuring they continue to decline thereafter. It identifies changes that help ensure a secure and affordable energy system in the long run, while also emphasising that transforming the energy sector is vital but not solely capable of meeting the ultimate goal. Substantial effort must also be made to reduce CO_2 and GHG emissions in non-energy sectors. The 2DS is broadly consistent with the *WEO* 450 Scenario (referring to concentration levels of 450 parts per million in the atmosphere).

Note: 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/etp2015.

For a decarbonisation of the energy system in the long term, inter-relations among the energy sectors become more important. The focus of *ETP 2014* was on the electricity system and the role a low-carbon electricity sector can play for deep emissions reduction in end-use sectors, such as transport. *ETP 2015* focuses in this chapter on ways to decarbonise heating and cooling as well as possible synergies and interactions between electricity and heating systems.

Figure 1.1 ESCII in *ETP* scenarios



Note: Figures and data that appear in this report can be downloaded from www.iea.org/etp2015.

Key point *Ambitious efforts are needed to reduce the carbon intensity of the global energy sector, with the challenge being slightly higher in OECD countries than in OECD non-member economies.*

Global modelling results

Transforming the global energy system to reach the 2DS requires further efforts to decouple energy use and economic activity, while also reducing environmental impacts at the same time. *ETP 2015* continues to examine the interface of technology, policy and financing needed to achieve the transformation, but also explores how other factors such as behavioural change (e.g. modal shift in the transport sector) can contribute (Box 1.2). Two strategies have to be pursued in parallel: improving energy efficiency to temper demand growth and reducing the carbon impact of the remaining required supply.

By 2050, energy efficiency in the 2DS leads to a 64% reduction in energy intensity of GDP compared to today; i.e. although global GDP more than triples, primary energy use increases by only 20% (Figure 1.2, left). Today, energy intensity of GDP varies widely among countries, with an average of 4.9 megajoules for each dollar of economic value (MJ/USD) in OECD countries and 8.2 MJ/USD for the aggregate OECD non-member economies.[3] In the 2DS, the energy intensity of both regions converges towards similar levels of 2.2 MJ/USD (OECD members) and 2.5 MJ/USD (OECD non-members). As energy demand and economic growth are expected to stagnate in the former, but expected to grow rapidly in the latter, larger decoupling efforts are needed in OECD non-member economies.

Reducing overall primary energy use is insufficient to attain the 2DS targets; as illustrated by the ESCII, the energy mix must also be altered to reduce CO_2 intensity (Figure 1.2, right) by around 60% by 2050. Whereas progress has been made in reducing the energy intensity of GDP, no improvements in the global CO_2 intensity of primary energy can be observed over the past decade. Improvements along both routes – reducing overall demand and decarbonising the remainder – have to be realised. On a regional level, differences in CO_2 intensity of primary energy use are less pronounced than for energy intensity of GDP, with 59 kilogrammes of CO_2 per megajoule ($kgCO_2/MJ$) in the OECD members and 66 $kgCO_2/MJ$ for OECD non-members in 2012. CO_2 intensity reductions in the 2DS by 2050 will need to be around three-quarters in the OECD members and two-thirds in OECD non-member economies.

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[3] GDP numbers are based on purchasing power parities (PPP) in real 2013 USD. They do not yet take into account revised PPP data for 2011, released by the World Bank's International Comparison Program in 2014.

Box 1.2 How has the 2DS changed between *ETP 2014* and *ETP 2015*?

ETP 2015 scenarios have been updated since 2014, particularly on key assumptions underlying the analysis such as energy prices, technology development, etc.; assumed projections for the socio-economic drivers of population and GDP are unchanged.*

Overall, the 2014 and 2015 scenario results align quite closely, but some changes are noteworthy. In each instance below, the format is to first give 2015 results in comparison with those from 2014. All results reflect the 2DS in 2050, the central scenario of *ETP* analysis.

- Primary energy demand is 3% lower, mainly due to lower use of biomass in power generation and end-use sectors, which reflects a revision of biomass supply-cost assumptions in *ETP 2015*. Still, biomass maintains its position as the largest energy carrier within a global primary use of almost 150 EJ in 2050, driven by increased consumption in transport and industry compared to today.
- Global final energy demand is 1.5% lower, mainly due to the mentioned biomass revision, whereas electricity generation remains largely stable. The generation mix, however, slightly deviates with wind accounting for 17% (instead of 18%), mainly due to slower deployment of offshore wind. Together with a slightly lower contribution from hydro, the overall renewable share falls to 63% (rather than 65%), mainly compensated by a higher share in fossil fuel-based generation (both with and without CCS).
- Annual global CO_2 emissions in the 2DS in 2050 are, at 14.4 $GtCO_2$, around 0.6 Gt lower than in *ETP 2014*; this mainly reflects small changes in the emissions trajectory to compensate for slightly higher emissions in the period 2015-20.

The recent plunge in oil prices – of around 60% from highs in June 2014 to levels seen in January 2015 – is not reflected in *ETP 2015* scenario analysis. Being long term in nature, the *ETP* modelling framework is not well suited to capture short-term imbalances in oil supply and demand, or their impact on prices. When and how oil markets will rebalance is still too uncertain to include in the long-term scenarios.

This does not mean that low oil prices would not affect the transition to a clean energy system. Most likely, a long period of low prices would be negative, stimulating oil consumption and leading to increased emissions (e.g. in the transport sector). While many regions no longer use oil for power generation, the practice of indexing gas and oil prices could increase the attractiveness of gas-fired generation while reducing interest and investment in renewable power projects.

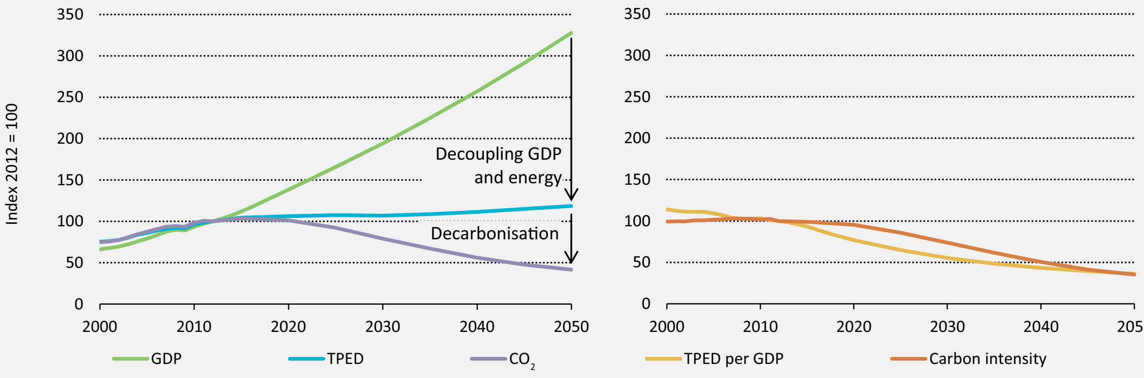
But low oil prices can also create opportunities for policy makers. Countries with fossil fuel subsidies could use this as an occasion to reform such schemes with lower impacts on consumers. Low fossil fuel prices could also provide the opportunity to introduce or strengthen carbon pricing instruments to foster energy efficiency or low-carbon energy sources.

* Population projections are based on the most recent United Nations population projections (UNDESA, 2013), which are updated every two years, with the next projection to be released in the first half of 2015. The GDP projections will be updated in *ETP 2016*, taking into account also revised power purchasing parities data for 2011, released by the World Bank's International Comparison Program in 2014.

Primary energy use

Primary energy use has grown by almost one-third over the decade 2002-12, with the increase almost fully covered (86%) by coal, oil and natural gas. Under the 6DS, the growth in total primary energy use continues, though at a slower rate, with global primary energy use in 2050 being 67% higher compared with 2012 (Figure 1.3). Improvements in the efficiency of fossil fuel use in the power sector and in end-use sectors, combined with increased use of renewable energy sources, helps to reduce overall dependency on fossil fuels, but they still supply 75% of the increase in primary energy use. In the 4DS, which

Figure 1.2 Development of global GDP, primary energy and CO_2 emissions in the 2DS



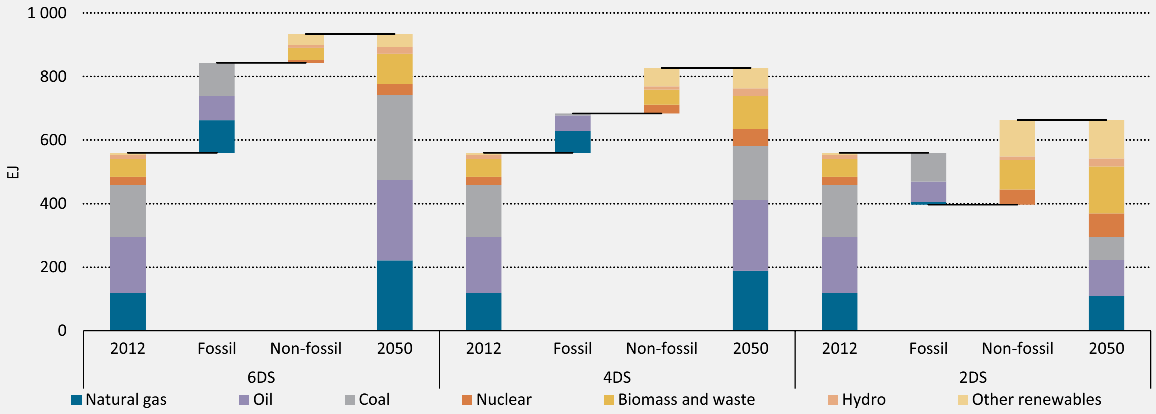
Note: TPED = total primary energy demand.

Key point *While efforts to decouple economic growth and primary energy use need to be accelerated, the larger challenge is to sufficiently reduce the CO_2 intensity of primary energy in the 2DS.*

includes proposed policy efforts to reduce GHGs, absolute growth in primary energy can be reduced to 48% by 2050 relative to 2012, with higher shares of renewables meaning that fossil fuels meet only half of this increase.

Limiting growth in fossil primary energy use is not sufficient to reach the ambitious climate targets of the 2DS; their share must actually be pushed to below current levels. In 2050, combined consumption of coal, oil and gas must be one-third lower than in 2012 while efforts across all energy sectors are needed to limit the unabated use of fossil fuels (i.e. without CCS).

Figure 1.3 Global primary energy use

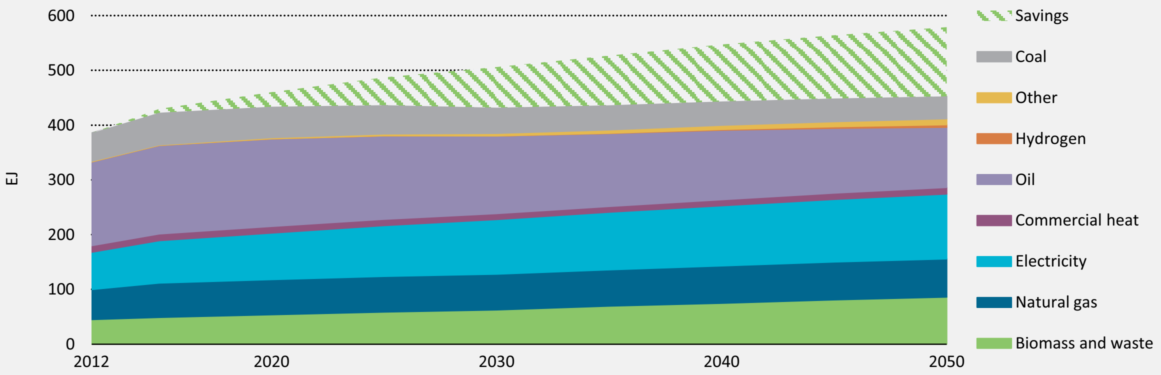


Key point *Fossil fuel remains dominant in primary energy use in 2050 in the 6DS and 4DS, but falls to below 2012 levels in the 2DS.*

Final energy consumption

Improving energy efficiency in buildings, industry and transport is key to the 2DS targets, and is often already a cost-effective measure to curb fossil energy use and emissions. In the 2DS, final energy consumption of all three sectors combined can be reduced by 30% by 2050 compared with the 6DS. Against current efficiency levels, further end-use improvements in the 2DS provide annual energy savings of 126 EJ by 2050, an amount representing 28% of the global final demand in 2050 in the 2DS and being almost equal to the 2012 combined final energy consumption of China and the European Union (Figure 1.4). Depending on which fuels are saved through efficiency improvements, corresponding reductions would be seen in either direct emissions in end-use sectors (e.g. in the case of fossil fuels, by replacing an old gas boiler with a new condensing one), or in indirect emissions further upstream (e.g. in the case of electricity savings, depending on the generation mix, reducing the use of fossil fuels in the electricity sector). In the 2DS (compared with the 6DS), energy efficiency across all end-use sectors accounts for direct and indirect emissions reduction of 290 $GtCO_2$ between 2012 and 2050, representing almost 40% of the cumulative reduction needed.

Figure 1.4 Impact of energy efficiency on global final energy consumption in the 2DS



Notes: The calculation of the final energy savings is based on a decomposition analysis to estimate the energy savings due to future efficiency improvements compared with the efficiency levels in 2012. The analysis attempts to isolate energy efficiency improvements from structural change and changes in activity that affect energy consumption and energy intensity (IEA, 2014b). The decomposition analysis includes the buildings, transport and industry sectors, but within industry includes only energy-intensive sub-sectors (not the low-intensity sub-sectors). Therefore, the estimated energy savings in the 2DS should be regarded as a lower bound on the contribution from energy efficiency. The category "Other" includes solar and geothermal final energy sources.

Key point *Aggressive energy efficiency improvements in the 2DS help to keep final energy demand in 2050 at 2012 levels.*

Fuel switching is another option to reduce CO_2 emissions in end-use sectors. Switching to less carbon-intensive fossil fuels – e.g. replacing coal or oil with natural gas – delivers some reduction in the short term, but should be seen only as a transition measure. From 2030 onwards, relative to low-carbon resources, even natural gas becomes more carbon-intensive than the average electricity mix needed to meet 2DS objectives. A more important option, therefore, is the switch to final energy carriers based on low-carbon sources. This can mean switching to renewables (such as solar thermal water heating in buildings or biofuels in transport) or using low-carbon electricity, heat[4] or hydrogen that are generated

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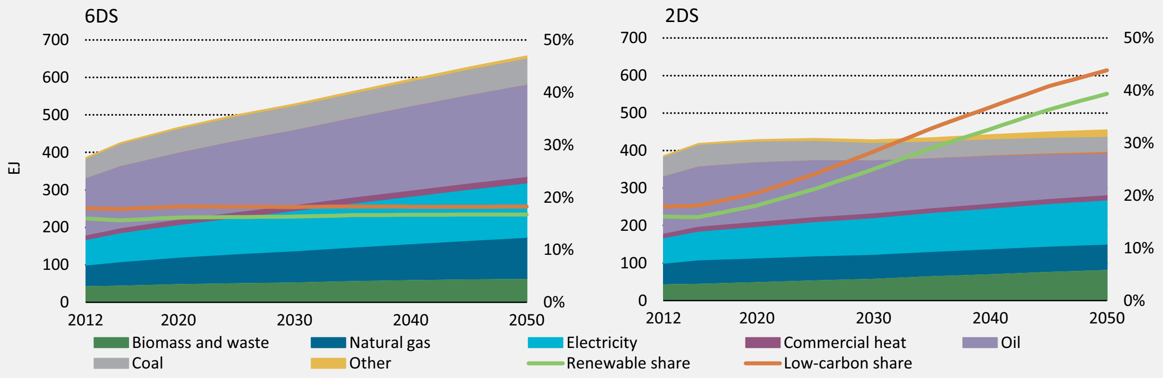
[4] Heat represents here commercial heat generated in co-generation or heat plants and sold to consumers in the buildings or industry sectors, with co-generation referring to the combined production of heat and electricity. Heat generated within buildings or on industrial premises for covering own heating needs is not included here.

from renewables, nuclear power or fossil fuels in combination with CCS in the power sector. In the 2DS, the share of low-carbon energy sources in the final energy mix more than doubles from 18% in 2012 to 44% in 2050 (Figure 1.5). The major part of the low-carbon final energy demand is based on renewables, accounting for 40% of the total final energy demand in 2050. Roughly half of this share is due to the direct use of renewable energy carriers (such as solar thermal energy or biofuels); the other half is linked to the contribution of renewables in generating electricity and commercial heat, consumed as final energy by the end-use sectors.

Low-carbon electricity plays a crucial role in reducing emissions in the end-use sectors: switching from fossil fuels to low-carbon electricity (e.g. through EVs) often meets the dual goal of reducing emissions and increasing overall energy efficiency. In the 2DS, global growth in electricity demand between 2012 and 2050 is three times higher than the growth in total final demand. As such, electricity becomes the largest final energy carrier (ahead of oil products), accounting for more than 25% of the total final energy consumption (against 18% in 2012). Despite this trend towards larger shares of electricity in the final energy mix, absolute demand for electricity in buildings, industry and transport combined in 2050 declines by almost 20% in the 2DS compared with the 6DS, corresponding roughly to reduced generation capacity needs in the power sector of 1 900 gigawatts (GW).[5] This highlights the importance of minimising inefficient use of electricity in end-use sectors, which is often a cost-effective near-term option to reduce emissions in the power sector.

Figure 1.5

Low-carbon and renewable shares in the global final energy demand in the 6DS and 2DS



Notes: The low-carbon share includes the direct use of final renewable energy sources (biomass, solar, geothermal), and also takes into account the share of low-carbon technologies (renewables, nuclear, CCS) in providing final electricity and commercial heat demands.

Key point *Renewables provide 40% of the 2DS global final energy demand in 2050; taking into account also electricity, heat and hydrogen generated from nuclear and CCS, 44% of final energy is based on low-carbon energy sources.*

CO_2 emissions

Global energy-related CO_2 emissions grew by 30% over the last decade. A portfolio of technology options across all sectors is needed to alter this emissions trajectory in a way consistent with the 2DS (Figure 1.6). End-use energy efficiency could provide almost 40%

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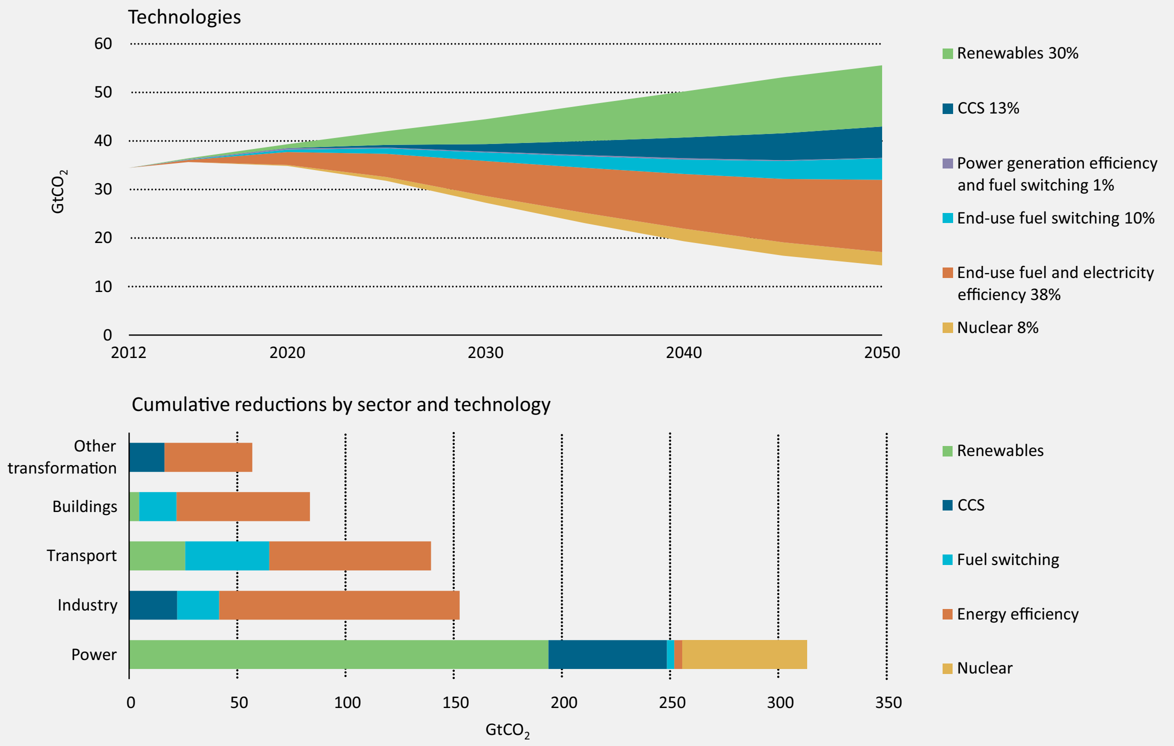
[5] Based on electricity savings of 7 600 terawatt hours (TWh) and 4 000 average full-load hours.

of the cumulative emissions reduction needed to move from the 6DS to the 2DS pathway, and accounting for 50% to 75% of the cumulative emissions reduction within the different end-use sectors.

Figure 1.6 Contribution of technology area and sector to global cumulative CO_2 reductions between 6DS and 2DS



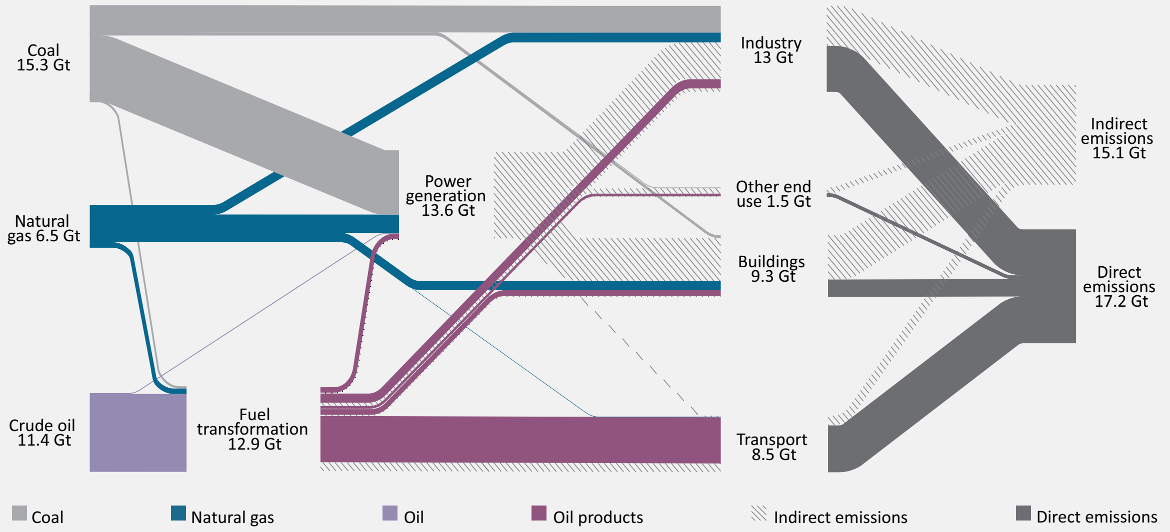
Notes: Percentage numbers represent cumulative contributions to emissions reduction relative to the 6DS. End-use fuel and electricity efficiency includes emissions reduction from efficiency improvements in end-use sectors (buildings, industry and transport), and in end-use fuels (including electricity). End-use fuel switching includes emissions reduction from changes in the fuel mix of the end-use sectors by switching from fossil 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, end-use sectors). Power generation efficiency and fuel switching includes reduction from efficiency improvements in fossil electricity, co-generation 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 *A portfolio of low-carbon technologies is needed to reach the 2DS; some solutions will be broadly applicable, while others will need to target specific sectors.*

The electricity sector accounts today for around 40% of global annual CO_2 emissions. Allocating emissions from electricity generation (as well as from other transformation sectors) as indirect emissions to the end-use sectors consuming the electricity shows that, especially for industry and buildings, the indirect emissions constitute a large part of the overall emissions for which these sectors are responsible (Figure 1.7). Improving the efficiency of electricity uses in industry and buildings is one way to mitigate these emissions while also achieving further fuel savings in power generation and often reducing capacity and investment needs in the power sector. The CO_2 reductions triggered by electricity savings in the end-use sectors account for 12% of the cumulative emissions reduction to reach the 2DS.

Electricity generation itself is drastically decarbonised in the 2DS, with global average CO_2 intensity plummeting from 533 grammes of CO_2 per kilowatt hour (gCO_2/kWh) in 2012 to less than 40 gCO_2/kWh in 2050. This allows increased use of low-carbon electricity (such as in heat pumps or EVs) to become an important option to reduce emissions in the end-use sectors. This reiterates the *ETP 2014* finding that the combination of decarbonised electricity generation and increased electrification of end uses is an important strategy to reduce emissions while also improving overall energy efficiency.

Figure 1.7 Direct and indirect CO_2 emissions in the global energy system in 2012 from an end-use sector perspective



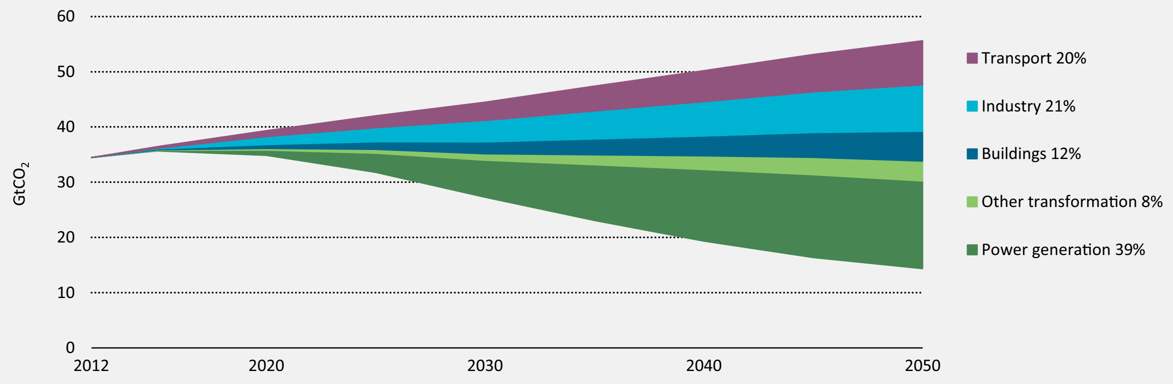
Notes: Direct emissions refer to CO_2 emissions from fossil fuel use in the end-use sectors; indirect emissions refer to upstream emissions from the end-use sectors occurring in the power and fuel transformation sectors. In contrast to the *ETP* scenarios, only energy-related emissions are covered here (but no process emissions). Total CO_2 emissions on the right-hand side are with 32.3 Gt higher than the value in the IEA CO_2 statistics for the *sectoral approach*; the deviation is due to small differences in the transformation sector. Numbers shown on the left-hand side correspond to the CO_2 statistics according to the *reference approach* in IEA statistics; their sum is 33.1 Gt and mainly due to statistical differences higher than the CO_2 emissions obtained from the *sectoral approach*.

Key point *Indirect emissions linked to electricity use are a major part of the CO_2 emissions arising from the buildings and industry sectors today.*

Sector development in the future energy system

The transition to the 2DS requires actions to be taken in all sectors within the energy system: efforts on either the supply side (power generation and other transformation) or end-use side (buildings, industry, transport) alone will deliver only around half of the reductions needed (Figure 1.8). The following section summarises the transition in the *ETP* scenarios for the four key sectors of electricity generation, transport, industry and buildings, in each case examining the current status, scenario results and actions needed.

Figure 1.8 Global CO_2 reductions between 6DS and 2DS by sector



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

Electricity generation

Current status

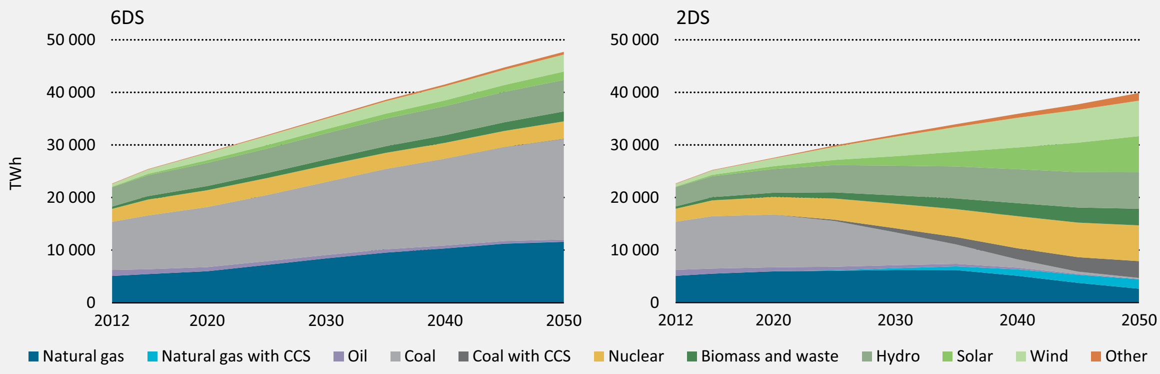
The power sector is responsible for around 40% of global primary energy use and CO_2 emissions. Electricity generation on a global level grew by 2.2% in 2012, somewhat lower than the 3.4% average annual growth rate over the last decade. Electricity covered 18% of the global final energy needs in 2012, i.e. energy consumed by the industry, buildings, transport and agriculture sectors. It is noteworthy that growth in final electricity consumption has been larger than the annual increase seen in final coal, gas or oil consumption. Electricity growth in 2012 was driven by OECD non-member economies, in particular by China, which in 2011 became the largest electricity producer globally. By contrast, electricity generation in many OECD countries stagnated in 2012, in line with recent trends.

Renewable energies have led growth in electricity generation, accounting for almost two-thirds of the generation growth in 2012 and outpacing for the first time ever the increase from fossil fuels. Despite this growth in renewables, fossil fuels continue to dominate with a share of 68% in the generation mix.

Scenario results

Under the 6DS, strong dependency on fossil fuels continues; by 2050, 65% of global electricity is still produced by fossil fuels (Figure 1.9) and the average CO_2 intensity is 480 gCO_2/kWh (compared with 533 gCO_2/kWh in 2012). A drastically different pathway evolves under the 2DS; electricity generation in 2050 is around 15% lower, driven by a 20% reduction in final electricity consumption (which is partly offset by electricity demand for producing hydrogen being used in the transport sector). The remaining electricity generation is virtually decarbonised by 2050, with average global CO_2 intensity dropping to less than 40 gCO_2/kWh. Renewables dominate in the 2DS with a 63% share in the global generation mix, with wind and solar photovoltaic (PV) together accounting for 26%. Nuclear generation accounts for 17% and fossil fuels in CCS plants for 13%. Only 7% of electricity is produced in fossil power plants without CCS, mainly gas plants running with relatively low full-load hours to balance generation from variable renewable sources.

Figure 1.9 Global electricity generation mix



Key point *Today fossil fuels dominate electricity generation with a 68% share of the generation mix; by 2050 in the 2DS, renewables reach an almost similar share of 63%.*

The variable nature of renewable generation requires sufficient flexibility in the electricity system to either absorb surpluses or compensate when electricity production from variable sources cannot keep pace with demand. On the generation side, flexibility can be provided by gas-fired power plants or by dispatchable low-carbon technologies, such as solar thermal electricity (STE), biomass or geothermal plants. Other flexibility options within the electricity sector include electricity storage or using transmission lines or interconnectors to create larger balancing areas. Other parts of the system can also serve as flexibility assets. Demand response measures (e.g. smart charging of EVs) can help to shift consumption to hours with surplus variable renewable generation. Linking the electricity system with the heat system (see also the section “Linking heat and electricity systems”) or with fuel production (such as electrolysis of hydrogen) can be further options for balancing variable renewables.

Strategies to decarbonise the electricity system depend on local opportunities, resource endowments and policy conditions (Figure 1.10). By 2050 in the 2DS, fossil fuels with CCS account for one-quarter or more of the generation mix in the Middle East, Eastern Europe, the former Soviet Union (FSU) and parts of Asia, while renewables have the potential to cover more than two-thirds of the mix in Africa, OECD Americas, the European Union and Latin America. Nuclear power also has a diverse expansion profile, reaching a share above the world average of 17% in the European Union, China, India, and parts of Eastern Europe and the FSU.

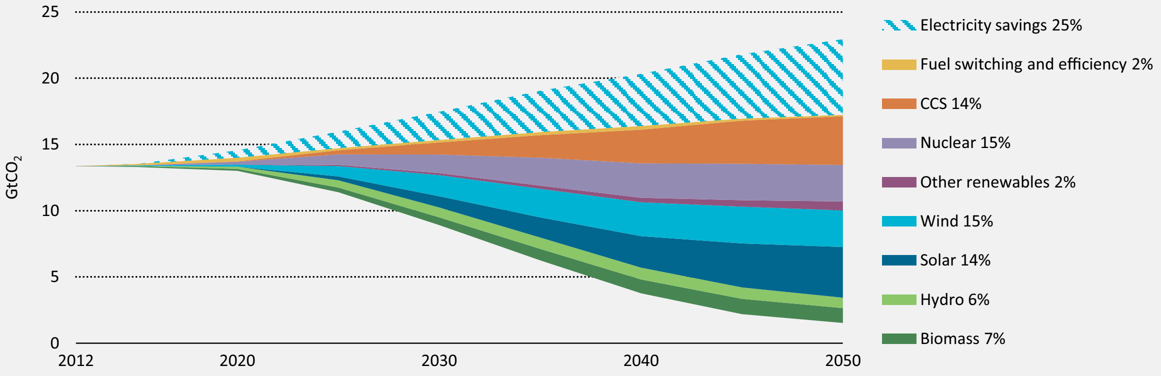
Cumulative CO_2 emissions from the power sector over the period 2012-50 are more than halved in the 2DS compared with the 6DS – but more than one-quarter of the reductions arise from electricity-saving measures in the end-use sectors (e.g. through more efficient electric appliances) rather than from power sector initiatives (Figure 1.11). Renewable energy technologies combined provide 44% of the cumulative reduction between the 6DS and 2DS; nuclear and CCS each deliver around 15%. Drivers such as rising fossil fuel prices and technology cost reductions stimulate deployment of several low-carbon technologies (e.g. nuclear, solar PV and onshore wind) in the 6DS and thus provide already in this scenario reductions over time, which amount to an annual reduction of 4 Gt in 2050 (or 20% of annual power sector emissions).

Figure 1.10 Evolution of regional electricity generation mixes in the 2DS

Note: STE = solar thermal electricity.

Key point *Opportunities to decarbonise the electricity generation mix depend on local conditions, but all regions show dramatic decarbonisation in 2050 compared with today.*

Figure 1.11 Key technologies to reduce power sector CO_2 emissions between 6DS and 2DS



Note: Percentage numbers refer to the contribution of the technology area to the cumulative CO_2 reduction between the 6DS and 2DS over the period 2012-50.

Key point *Electricity savings in the end-use sectors would stabilise power sector emissions at levels slightly above today's; a portfolio of low-carbon generation technologies is needed to sufficiently decarbonise electricity for 2DS targets.*

Key actions

Given the long technical lifetime of power generation technologies, avoiding lock-in of carbon-intensive technologies is critical. From the coal power plants currently operating or under construction, some 1 000 GW of coal capacity could still operate in 2050 and emit around 3.5 $GtCO_2$ annually – a volume more than double the allotted power sector emissions of 1.5 $GtCO_2$ in the 2DS. This illustrates that early retirement of coal capacity or retrofits with CCS are unavoidable. New coal capacity being built, if not equipped with CCS from the outset, should be designed for future CCS retrofits, i.e. taking into account space requirements for capture-related equipment and proximity to a future storage site in locating the plant.

Incorporating higher shares from variable renewables and supporting electrification of end-use sectors will increase the flexibility needs of the electricity system. Integrated energy system planning can help to identify the suitable mix of the four main flexibility measures (flexible generation, electricity storage, interconnectors and demand response) within a given electricity system and possible balancing options external to the electricity system (e.g. district heating systems or fuel production). Policy makers can support the planning process through integrated energy system studies, providing guidance to the different actors in the system, and follow on 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.

Strong carbon pricing is a key component of decarbonisation efforts, with projected prices in the 2DS needing to be in the range of USD 100 per tonne of CO_2 (tCO_2) by 2030 and USD 170/tCO_2 by 2050. If carbon prices are lower, additional measures will be necessary to trigger the low-carbon investment needed in the power sector. Governments will have to continue providing policy solutions that improve the net present value of low-carbon investments and mitigate the market risks for project developers and financial investors. This support is particularly important for demonstration projects for new technologies moving through the transition from pilot to large-scale deployment.

Transport

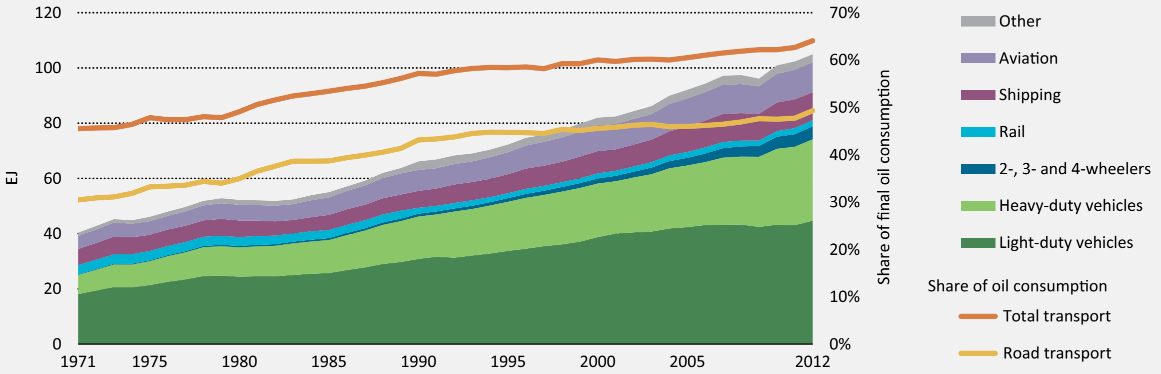
Current status

The transport sector accounted for 27% of total global final energy consumption in 2012 and 20% of global energy- and process-related CO_2 emissions. Transport emissions have been driven by strong continued growth in energy demand for passenger light-duty vehicles (PLDVs) and heavy road vehicles (Figure 1.12). Approximately 75 million new PLDVs were added to roads in 2012.

Overall, the transport sector consumes nearly two-thirds of final global oil consumption, having increased nearly by 25% since 2000, while oil consumption in power, industry and buildings stagnated or even declined over this period. The years 2012 and 2013 also marked important changes in road transport: as of 2012, road transport alone accounted for half of total final global oil demand, and since 2013, sales of all road vehicles (including PLDVs, trucks and buses) in OECD non-member economies have exceeded those of the OECD members.

Continued heavy reliance on oil in the transport sector stresses the need for strong new policies to change course in favour of low-carbon transport. The transport sector is still more than 90% dependent on oil products, a level practically unchanged since the 1970s as increased road travel, aviation and shipping demand have offset any switching to other energy carriers, such as the sixfold increase in biofuels use since 2000 and ongoing electrification of the rail sub-sector (Figure 1.13). Oil use in road transport decreased slightly to 95% of road transport energy demand in 2012 (from 98% in 2000), as many countries introduced alternative-fuel vehicles along with new or improved fuel economy standards. Still, much greater effort is needed to reduce oil dependence and put transport on track to meet 2DS targets by 2050.

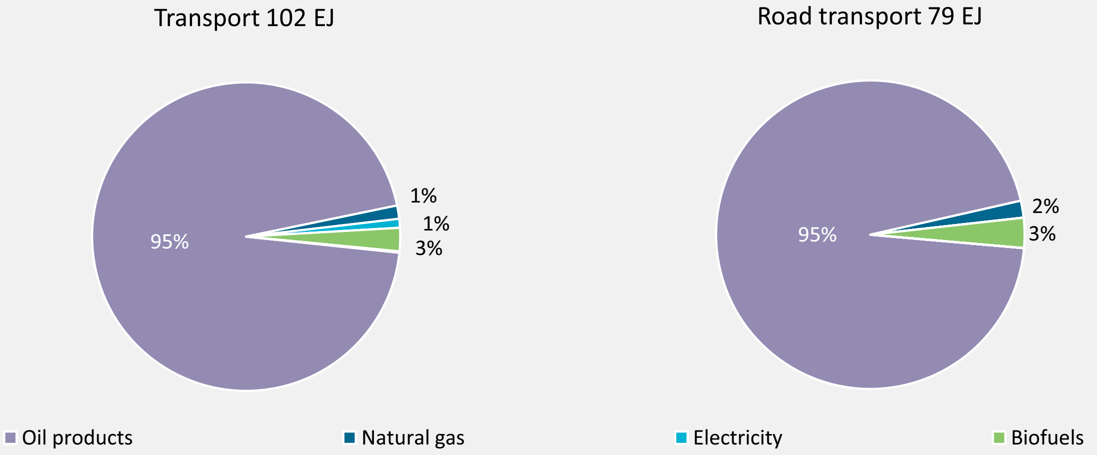
Figure 1.12 Global transport energy consumption by mode



Notes: Light-duty vehicles are cars and light trucks (up to 3.5 tonnes); heavy-duty vehicles are trucks and buses. Aviation and shipping include international bunkers, i.e. fuels used for international aviation and navigation.

Key point *Global transport accounts for nearly two-thirds of total final global oil consumption, with road transport representing three-quarters of transport energy consumption.*

Figure 1.13 Global transport energy consumption by fuel type in 2012

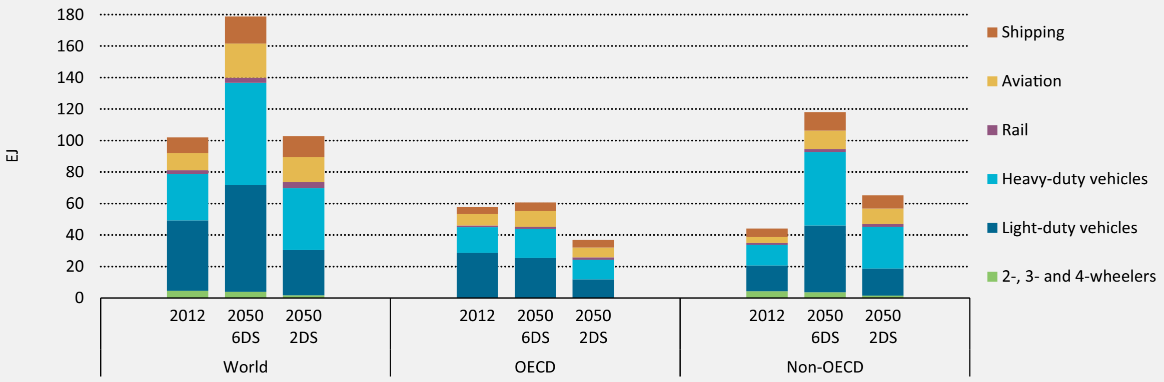


Key point *Despite fuel economy measures and the introduction of alternative fuels, transport remains highly dependent on oil products.*

Scenario results

In the absence of rapid changes in vehicle technology shares and the modal mix, the share of total final global oil demand consumed by transport will continue to rise over the next decades, as will the importance of road transport in the total energy use for transportation services. Without action, global transport energy demand is expected to increase nearly 75% over 2012 levels by 2050 (Figure 1.14). Transport energy consumption in OECD countries is expected to remain relatively stable to 2050 in the 6DS as a result of existing fuel economy standards and diminishing growth in new travel demand. By contrast, transport energy use in OECD non-member economies surges by more than 150% as mobility demand and private motorisation continues to increase. PLDV and heavy-duty vehicle energy consumption in OECD non-member economies is expected to increase threefold.

Figure 1.14 Transport energy consumption by region



Note: Light-duty vehicles are cars and light trucks (up to 3.5 tonnes); heavy-duty vehicles are trucks and buses.

Key point *Global transport energy use will increase nearly to 75% by 2050 without concerted action. Improved energy efficiency, paired with Avoid and Shift policies, is needed to curb this growth rate.*

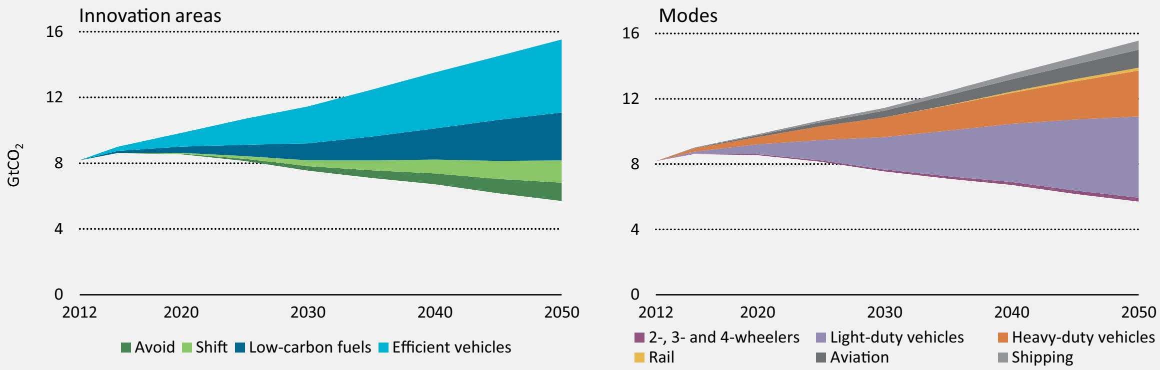
In order to reach 2DS targets, *ETP 2014* presented an **Avoid, Shift and Improve** strategy, which sought to reduce overall transport demand, shift remaining demand to low-carbon fuels and improve energy efficiency of all transport modes (IEA, 2014a). Under such a strategy, global transport energy demand stabilises by 2050 at approximately 100 EJ (a demand level comparable to today), while global annual transport emissions decrease by around 30% to less than 6 $GtCO_2$.

Strengthened fuel economy policies, incentives for alternative fuels and efficient vehicles, improved management of travel demand, and modal-shift policies will all play key roles in achieving transport emissions reduction targets in OECD countries. In OECD non-member economies, strategic planning and investments in low-carbon transport infrastructure will be critical to meeting rapid growth in mobility demand in a more sustainable manner, as will implementation and enforcement of vehicle fuel economy standards to mitigate road transport energy and emissions growth.

Avoid and Shift policies in the 2DS have the potential to reduce global transport energy consumption and emissions by 15% or more by 2050, primarily through better management of travel demand and by moving passenger and freight travel to more efficient modes. At the same time, more efficient vehicle technology and cleaner fuels are crucial to offset the impact of motorised transport growth to 2050 and meet 2DS emissions targets.

Significant effort is still needed to put the motorised vehicle market on a low-carbon pathway, especially as private mobility demand continues to grow rapidly in emerging economies. In the 2DS, innovation is crucial to deliver fuel savings and GHG emissions reduction in all transport modes (Figure 1.15). The most energy-intensive modes (namely road) also have the largest potential for improvement. Technology-based innovations (improving vehicle efficiency and fuel switching) play a major role in curbing emissions beyond reductions that can be achieved from land-use planning, travel demand management and modal shifting (Avoid and Shift).

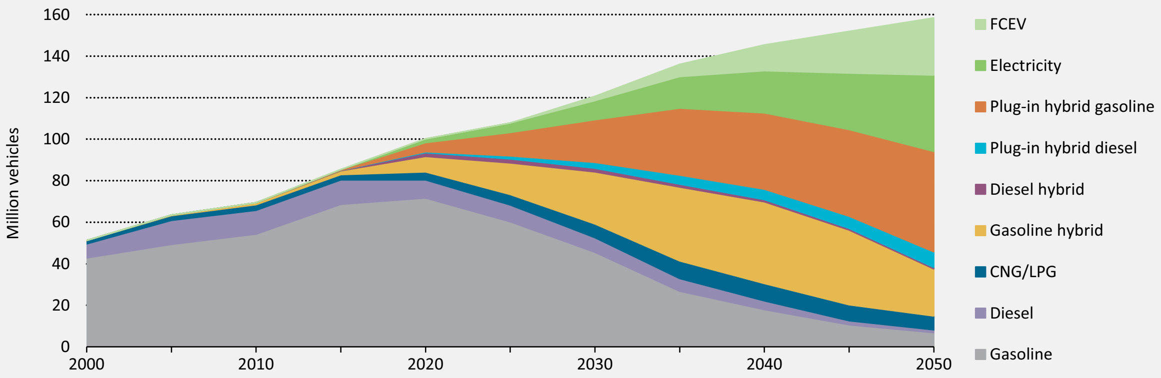
Figure 1.15 Contribution to well-to-wheel GHG emissions reduction between 6DS and 2DS by mode and innovation area



Key point *Vehicle efficiency improvements and fuel switching deliver a significant portion of GHG emission savings, with the largest savings being achieved in road transport modes.*

Emissions reduction potential in the PLDV market underscores the importance of technology development and deployment in the 2DS. Global sales of gasoline and diesel PLDV powertrains (even those that embed some innovative improvements) need to peak by 2020 and then rapidly decline as alternative fuels and more energy efficient vehicle technologies enter the market (Figure 1.16). By 2050, the average fuel economy of new PLDVs is halved compared with 2012, largely as a result of ongoing hybridisation of internal combustion engines (ICEs), complemented by solutions allowing the use of low-carbon energy carriers (such as electricity and hydrogen) on PLDVs. In 2050, the global portfolio of PLDV sales in the 2DS includes 60% PHEVs and EVs while sales of ICE and hybrid vehicles fall to just 20%. FCEV sales increase rapidly beyond 2030, reaching nearly 20% of market share by 2050. Multiple challenges still need to be overcome to bring these technologies to mass market in the coming decades, such as range limitations (for battery electric vehicles [BEVs]), costs and the availability of energy distribution infrastructure (especially relevant for hydrogen-based technologies).

Figure 1.16 Global portfolio of technologies for PLDVs in the 2DS



Note: CNG = compressed natural gas; LPG = liquefied petroleum gas.

Key point *The 2DS sees a dramatic change in PLDV technologies, with EVs, PHEVs and FCEVs accounting for nearly three-quarters of new vehicle sales in 2050.*

In the shipping, aviation and rail sub-sectors, the Avoid, Shift and Improve strategy seeks to reduce activity growth through measures such as replacing travel with greater use of information and communication technology, modal shifts to energy efficient high-speed connections, and continued energy efficiency improvements and alternative fuels – all of which help to mitigate energy and emissions growth (Box 1.3). By 2050 in the 2DS, the combined energy consumption of rail, shipping and aviation is reduced by 30% compared with the 6DS. Continued electrification of rail, along with energy efficiency improvements and increased use of alternative fuels (e.g. natural gas and biofuels) in shipping and aviation, stabilises their combined CO_2 emissions by 2025 and by 2050 delivers a 66% reduction compared with the 6DS.

Box 1.3 Aviation and shipping

The International Civil Aviation Organization (ICAO) has implemented two initiatives that are compatible with the GHG emission developments taken into account in the 2DS for aviation: a goal of 2% annual fuel efficiency improvement for international aviation has been extended to 2050, and a target added for carbon-neutral growth from 2020. Actually achieving carbon-neutral growth in aviation requires effort to reduce the well-to-tank carbon intensity of fuels and to encourage modal shifts towards less energy- and carbon-intensive modes. In the 2DS, low-carbon aviation fuels need to be deployed on a large scale before 2025, and must supply 14% of the total aviation energy use in 2050.

In maritime transport, the International Maritime Organization (IMO) has introduced the Energy Efficiency Design Index (EEDI) to support implementation of fuel efficiency standards for new ships. The EEDI standards for new ships will be implemented through four phases, progressively evolving towards a 30% improvement (compared with the 2013 baseline) by 2025. This rate is broadly consistent with the values stemming from the 2DS energy demand projections for shipping. Achieving GHG emissions reduction compatible with the 2DS targets for shipping will require additional savings from deployment of low-carbon fuel options, which account for 14% of the 2DS energy demand of ships in 2050.

Key actions

Diverse innovations are needed to meet 2DS transport objectives, including more efficient vehicles, alternative fuels and instruments that shift travel patterns towards more efficient modes. In the policy realm, instruments are needed that support management of travel demand, shift passenger activity to collective transport modes, and stimulate technological improvements on vehicles and fuels. Measures should target five key areas: reducing passenger transport demand; promoting shifts to more efficient modes; improving the energy efficiency of vehicles; enabling and encouraging the market introduction of promising technologies; and improving the characteristics of transport fuels with respect to GHG emission intensity.

Reduce passenger transport demand: the urban environment has significant impacts on travel needs of individuals, and therefore on the total transport activity. Urban and land-use planning instruments that favour compact urban development and mixed land use can reduce distances between origin and destination, delivering long-lasting energy savings as individuals travel less. The 2DS results include lower activity projections for road transport modes, reflecting changes that stem from such policy instruments.

Promote shifts towards energy efficient transport modes: modal choice has significant impacts on the energy efficiency of mobility. For passenger transport, high reliance on collective mass transit systems can guarantee wide access to mobility while delivering significant energy savings. Planning urban development to include high-quality and high-capacity public transport and mobilising investments to support deployment of public transport are examples of measures that can ultimately encourage individuals to choose energy efficient urban mobility solutions.

For both freight and passenger transport, investments in infrastructure development (when feasible in a cost-effective manner) and subsidies for their operation (when justified by net savings when transport externalities are accounted for) are particularly important to realise modal shift to efficient transport options.

Improve the energy efficiency of vehicles: fuel economy standards for all categories of road vehicles are effective “policy push” tools to direct technology innovation toward energy efficiency and carbon mitigation targets.

Complementary “market pull” measures, such as performance-based incentives and tax schemes (feebates), can influence decision making and accelerate market uptake of efficient, low-emitting vehicles. Energy efficiency labelling and consumer information campaigns are effective instruments to influence buyer behaviour.

Both fuel efficiency standards and differentiated vehicle taxation can stimulate deployment of the technology innovations needed to meet 2DS objectives for global vehicle fleet. In the short term, fuel economy standards can deliver the largest immediate savings by building on the deployment of already available, cost-effective technologies for 2-wheelers, PLDVs and heavy-duty vehicles.

Meeting 2DS targets requires scaling up the market coverage of fuel economy regulations on light and heavy road vehicles (including in all developed and developing economies that are likely to experience strong motorisation growth). Fuel economy regulations need to be introduced where they are currently lacking, strengthened where they exist and sustained over time in both contexts.

For cars, adoption of the Global Fuel Economy Initiative (GFEI) objective of a 50% reduction in new vehicle fuel consumption by 2030 (compared with 2005 levels) is consistent with 2DS targets, provided additional GHG emission savings can be delivered by low-carbon alternative fuels, including methane, advanced biofuels, electricity and hydrogen (taken together, alternative fuels account for 30% of the 2DS PLDV energy demand in 2050).

For trucks, meeting 2DS targets requires global adoption of regulatory measures capable of exceeding a 30% improvement in fuel consumption of heavy road vehicles by 2030. Again, this must be in conjunction with market penetration of alternative fuels (covering 22% of the energy delivered to trucks in 2050), as well as the reallocation of some long-distance road freight transport to rail and shipping.

The potential rebound effect from improved vehicle efficiency can be reduced by a broad set of measures, such as fuel taxation (including removal of fuel subsidies), carbon pricing, road charging, congestion pricing, parking fees and access restrictions, all helping to manage travel demand growth. If implemented jointly with instruments to reduce trip distances (such as integrated land-use and transport planning), such measures can be neutral with respect to mobility costs faced by consumers.

Enable and encourage market introduction of promising technologies: in the medium to long term, meeting the 2DS targets requires policy action to encourage mass deployment of more innovative technologies, such as EVs, PHEVs and FCEVs, as well as low-carbon fuels (Box 1.4).

Support and funding (policy push) for direct and technology-specific research, development and demonstration (RD&D) can help address the technical and cost-related barriers (such as energy storage capacity limitations, which affect driving range and charging time).

Market pull measures, such as technology-specific incentives, can influence consumer choices to accelerate market uptake of efficient, low-emission vehicles (including EVs, PHEVs, BEVs and hydrogen FCEVs). Their implementation should, however, be limited to the market deployment phase. Parallel measures, including fiscal incentives and financial instruments to mitigate risk, should target barriers that limit the rapid deployment of energy distribution networks (e.g. for EVs and hydrogen FCEVs).

If implemented in conjunction with technology push measures, market pull measures that target individual drivers (e.g. road charging, congestion pricing, parking fees and access restrictions) can also provide significant incentives to stimulate the market penetration of innovative technologies.

Box 1.4

Hydrogen deployment in the road transport sector

Making hydrogen FCEVs a viable alternative for consumers remains a substantial challenge. Although purchase costs of FCEVs are expected to drop quickly with the scale-up of sales, the cost of hydrogen at filling stations is expected to decline more slowly, due to the need for an entirely new infrastructure for hydrogen transportation, distribution and retail sales.

Substantial policy intervention is needed to make the total cost of driving FCEVs economically feasible. If, for example, hydrogen were exempted from fuel taxes and direct subsidies were used to ramp up the FCEV market, break-even status compared with high-efficiency conventional cars could be reached within about 15 years of the first 10 000 FCEVs being introduced.

This need for simultaneous FCEV market introduction and build-up of the hydrogen generation and refuelling infrastructure represents one of the most challenging elements of transport transformation in the 2DS.

Meeting the 2DS targets on hydrogen FCEVs requires a high degree of co-ordination among many stakeholders, including vehicle manufacturers, energy suppliers, utilities and grid operators, as well as local and national governments.

Improve the characteristics of fuels: fuel quality regulations, blending mandates and obligations for the provision of fuel distribution infrastructure can all be used to both improve the characteristics of individual fuels and promote fuel switching. Fuel quality regulations with GHG emission specifications are better suited to provide technology-neutral support across the life cycle of fuels, and are most relevant for transport fuels that are compatible with existing distribution infrastructure. Other, alternative fuel markets (e.g. hydrogen) will require technology-specific actions designed to support market introduction.

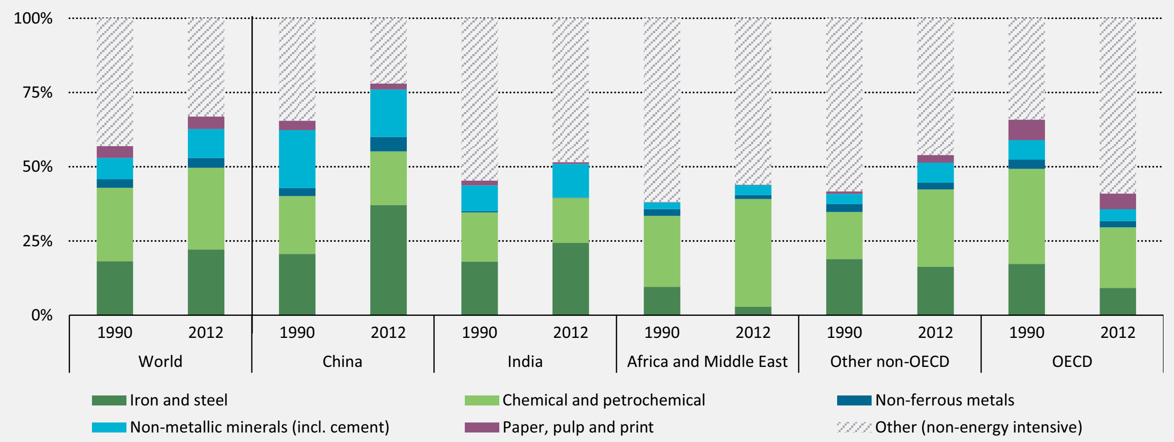
Industry

Current status

In 2012, the industrial sector showed a continuation of past trends with rising levels of energy use and direct emissions. While dramatic year-on-year changes in either measure are rare at the global level, these long-standing trends run parallel to increases in production and efficiency improvements. Overall production growth, however, has outweighed the efficiency gains, leading to 2012 showing the highest-ever absolute levels of industrial energy use (143 EJ) and CO_2 emissions (8.4 $GtCO_2$).

Growth in demand for certain materials has shifted industrial energy consumption towards energy-intensive sectors,[6] which now make up 67% of industrial energy use, compared with 57% in 1990 (Figure 1.17). This shift has pushed up energy use in the industrial sector, despite a partial offset by energy efficiency improvements. Overall aggregated industrial energy intensity per unit of value-added has improved 2% since 2011, and 12% since 2000.

Figure 1.17 Shares of industrial energy consumption



Key point *Energy-intensive sectors have gained share against non-intensive sectors since 1990 in all regions except OECD countries.*

A shift away from OECD countries as the centre of production has changed the profile of the industrial sector. China, for example, has steadily become a more important player in industry, more than doubling its absolute crude steel production since 2005 (accounting for 47% of global production in 2012, compared with 31% in 2005 and 15% in 2000). India and

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[6] Chemicals and petrochemicals, iron and steel, cement, pulp and paper, and aluminium.

other emerging Asian economies have also gained in market share; together they account for 13% of global industrial energy use compared with 8% in 1990.

While industrial capacity additions open opportunities to deploy best available technologies (BATs), rapid growth may pose challenges related to limited availability of recycled materials, the access to technologies and financing as well as the need for capacity building, which could limit the penetration of low-carbon process routes in regions experiencing rapid industrial growth.

Scenario results

While moderate industrial growth is projected in OECD countries to 2050, significant increases in demand for industrial materials are expected in many OECD non-member economies. This intensifies the need to decouple energy use from production. As China's material demand growth will slow and even begin to decline in some sectors, other OECD non-member economies will forge ahead with strong production growth as demand increases. Middle Eastern and African countries have strong emerging markets for cement and iron and steel demand, as do developing Asian countries, including India. Divergent regional energy prices and asymmetrical regional climate policies can pose a challenge for industries competing in global markets, as each region faces different economic pressures.

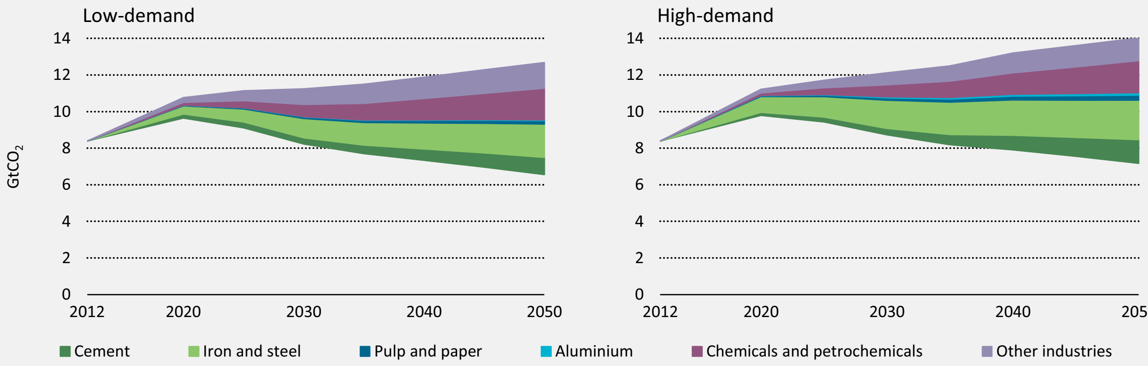
Managing process CO_2 emissions (i.e. those inherent to reactions during manufacturing), which accounted for 19% of total direct industry CO_2 emissions in 2012, poses an additional challenge. This is especially important in the cement sector, where process emissions accounted for 62% of direct CO_2 emissions of this sector in 2012. Process emissions cannot be reduced unless adequate alternative lower-carbon feedstocks are found or CCS is deployed. Despite improvements in material resource efficiency, global demand for most materials is expected to grow, intensifying the need to address both energy use and process emissions.

Availability of raw material – and also raw material degradation – are concerns in several energy-intensive sectors. Blast furnace slag availability, for example, can influence the feasibility of clinker ratio reductions for CO_2 savings in the cement industry, scrap metal availability can limit possibilities for recycling in iron and steel and aluminium, and declining iron ore quality can limit the potential to reduce energy intensity in crude steel production.

Despite these challenges, the 2DS requires that all industrial sectors dramatically reduce emissions through to 2050 (Figure 1.18) to achieve a total level of 6.6 $GtCO_2$ (against 8.4 $GtCO_2$ in 2012). While strong effort is required in all sub-sectors, absolute emissions reduction levels vary due to differing constraints, baselines and absolute sizes of sub-sectors. Of the energy-intensive industrial sectors, iron and steel makes the largest contribution (32%) to cumulative reduction of direct industry emissions in the 2DS, followed by 25% from chemicals and petrochemicals, 14% from cement, 3% from pulp and paper, and 1% from aluminium.

Considerable improvements in energy efficiency of industrial processes can be achieved in all sectors in the short to medium term, such that taken together with switching to low-carbon fuels, deploying BATs, and increasing recycling rates, such measures account for 88% of industrial emissions reduction in 2030. As manufacturing processes become less carbon-intensive and new processes become available in the long term, these changes provide only 73% of the overall reductions in 2050. Standardised data collection and monitoring of energy use and emissions at the technology and site level (e.g. through a variety of benchmarking and performance measurement programmes and practices) are needed to track progress on these measures (Box 1.5).

Figure 1.18 Direct industrial emissions reduction between 6DS and 2DS by sector



Note: The ETP industry model considers low-demand and high-demand variants for each scenario, to account for some of the uncertainty associated with long-term projections for industrial materials production. Numbers refer to the low-demand variant, unless otherwise noted.

Key point *Direct CO_2 industrial emissions peak in 2020 in the 2DS but continue to rise in the 6DS.*

Box 1.5 Monitoring CO_2 emissions in industry: An example from the iron and steel sector

ISO 14404, a standard from the International Organization for Standardization (ISO) that provides guidelines to iron and steel producers on CO_2 emissions measurement, is an example of how industry can start prioritising environmental performance targets and accurately account for their status in a standardised manner. ISO 14404 provides standard definitions of boundaries, material and energy flows, and emissions factors, along with a methodology for calculating both direct and indirect emissions, without requiring any installation of new equipment. It is complementary to other ISO standards, particularly those on energy management, and can be used with other energy and emissions measurement and management techniques.

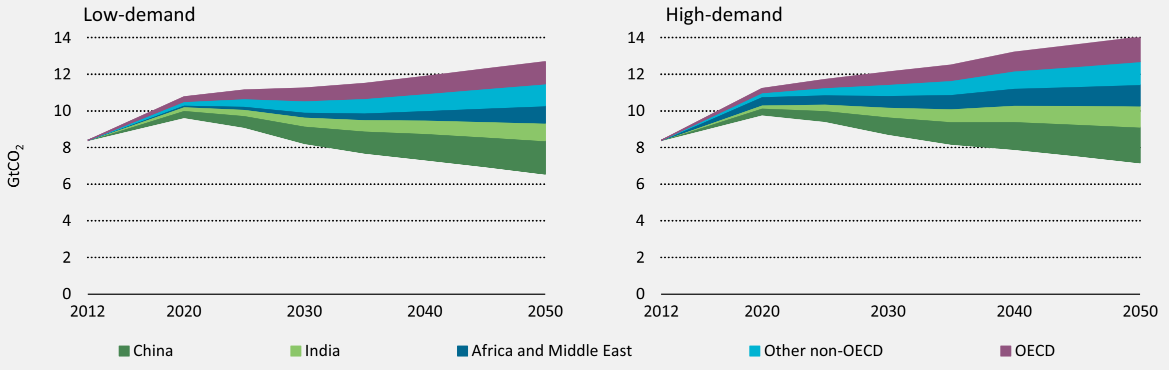
The Japanese Ministry of Economy, Trade and Industry (METI) and the Japan Iron and Steel Federation (JISF) have been promoting use of the standard in India and within the region of the Association of Southeast Asian Nations (ASEAN) in recent years, by sending experts to demonstrate the ISO 14404 accounting system and its benefits. These demonstrations are conducted alongside energy audits, which can identify opportunities for energy efficiency and energy savings, and measure the CO_2 emissions impacts of plant improvements and changes. Other methodologies and practices exist for monitoring emissions in the iron and steel sector, such as the World Steel methodology for emissions measurement.

Innovation across industry will play a critical role in achieving the 2DS goals, particularly in the long run. In 2050, innovative processes and technologies (including CCS) deliver 1.7 Gt of avoided CO_2, equalling 27% of overall industrial CO_2 emissions reduction in that year. Short-term actions to develop, demonstrate and deploy these technologies, especially CO_2 capture, are needed to ensure their availability in the longer term. In the 2DS, emissions reduction from innovative processes in the cement sector contributes savings of 12 million tonnes of CO_2 ($MtCO_2$) in 2030, which grows quickly to 467 $MtCO_2$ avoided in 2050. Most of these reductions in 2050 are from CCS applications. In the iron and steel sector, a number of innovative process routes now under development (including top gas recycling blast furnaces, Hisarna and Ulcored routes coupled with CO_2 capture) begin contributing in 2030 with 137 $MtCO_2$ avoided, which increases to an annual amount of 624 $MtCO_2$ in 2050. Some of the challenges and opportunities to drive industrial innovation for sustainability are analysed in Chapter 6.

Projected material demand growth and rising global market shares increase the long-term potential for BATs and innovative processes in OECD non-member economies. In the 2DS low-demand variant, China contributes the most (1 822 $MtCO_2$) to CO_2 emissions reduction in 2050 compared with the 6DS, followed by OECD countries (1 202 $MtCO_2$), India (961 $MtCO_2$), and Africa and the Middle East (946 $MtCO_2$) (Figure 1.19). Diffusion of low-carbon technologies in emerging economies is discussed in more detail in Chapter 7.

Figure 1.19

Direct industrial emissions reduction between 6DS and 2DS by region



Key point *OECD non-member economies account for 83% of the direct industrial emissions reduction in 2050 in the 2DS.*

Key actions

The industrial sector has made progress in terms of energy efficiency in recent years, but as absolute emissions levels continue to rise, further effort is needed to meet the 2DS targets. Policy makers and industry stakeholders could achieve short-term environmental benefits by focusing on improving energy efficiency, switching to lower-carbon and alternative fuels, and deploying BATs to the greatest extent possible. Creating internationally co-ordinated regulatory frameworks that are conducive to sustainable growth and address challenges such as industrial competitiveness and carbon leakage is vital. Instruments such as stable, long-term CO_2 pricing mechanisms and the removal of market distortions (such as fuel subsidies) could properly incentivise energy efficiency. Methods should be developed to reduce energy use and emissions in all industrial sectors, for instance, through legally binding GHG reduction targets supported by sustainable policy frameworks and business models.

Taking the next step, public and private sector actors should collaborate to aggressively pursue sustainable industrial innovation, in part by prioritising decisions and investments that facilitate the development and demonstration of low-carbon solutions. In order to drive longer-term innovation and technology deployment, policy and business strategies should adopt an integrated, systems-based approach across national and regional boundaries, taking into account the challenges industry faces and seeking solutions that promote environmental sustainability across the entire product life cycle.

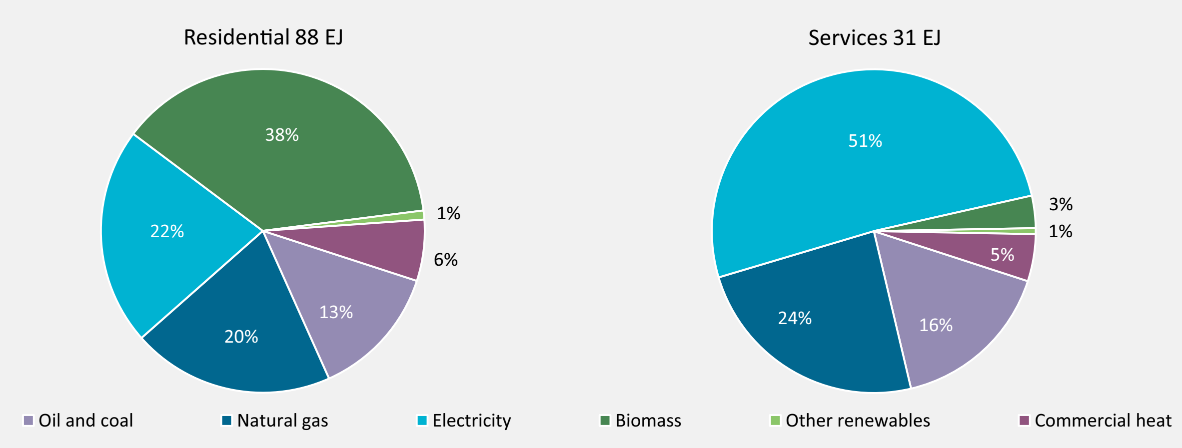
Buildings

Current status

The buildings sector, comprising both the residential and services sub-sectors, consumes almost 117 EJ, or over 30% of global total final energy consumption (Figure 1.20) and accounts for half of global electricity demand. When the upstream generation of electricity and heat in the power sector is taken into account, the sector relies almost 60% on fossil energy sources and is responsible for almost 30% of global CO_2 emissions. Despite significant policy efforts to slow energy demand growth in buildings, it has risen by nearly 20% since 2000, while population has grown by almost 16% and GDP has increased by around 50%.

Energy policy has started to decouple building energy demand growth from population and GDP, but much more effort is needed. While decoupling can be observed over the last decade in many OECD countries with stagnating buildings energy demand, demand in OECD non-member economies combined grew by 30% between 2000 and 2012. Considering the current high dependence on fossil fuels to generate electricity (68%) and their direct use in buildings for heating, the buildings sector has a long way to go before it can achieve a low-carbon footprint.

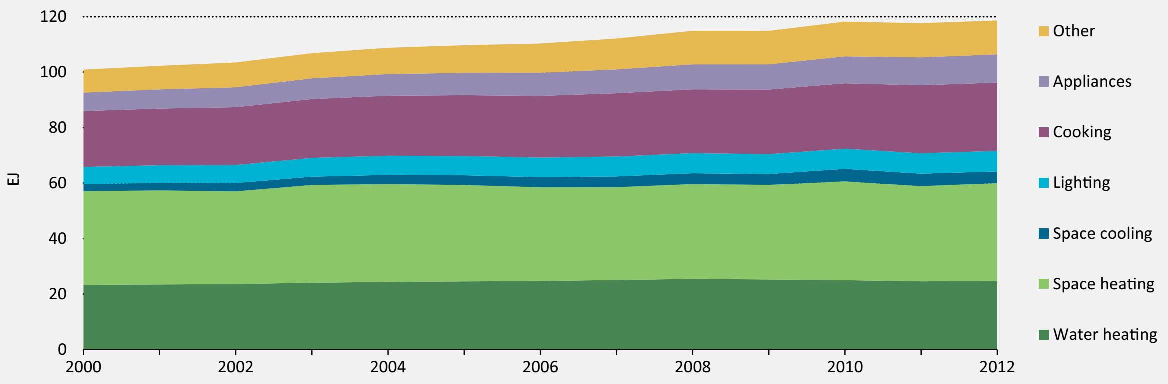
Figure 1.20 Final buildings energy consumption by fuel share in 2012



Key point *Direct fossil fuel use accounts for only 36% of final energy consumption in buildings; including the fossil generation share of electricity and heat in the power sector drives the fossil share upward to almost 60%.*

While all end-use impacts are important, space and water heating represent the largest portion (50%) of energy consumption in the buildings sector (Figure 1.21). In many regions, the lack of access to modern energy sources means that traditional biomass for cooking and heating continues to represent a significant portion of residential consumption, accounting for 37% globally. In addition to the task of collecting fuelwood for cooking being not only onerous, indoor air pollution from cooking often disproportionally impacts the health of women and children.

Figure 1.21 Final buildings energy consumption by end use



Key point *Space and water heating represent half of the final energy consumption in the buildings sector.*

Scenario results

Without action to improve energy efficiency in the buildings sector, final energy demand is expected to rise by 56% by 2050 in the 6DS (Figure 1.22). The main drivers of this rapid growth are expected increases in population by more than one-third and in global average GDP per capita by 140% compared with 2012. These drivers will result in an increase of more than 50% in the number of households by 2050 and a doubling of global residential floor area, while floor area in the services sector grows by more than 60%.

China and India are each responsible for one fifth of the buildings energy demand growth in the 6DS, while demand in industrialised countries increases only slightly or stagnates (consistent with recent trends). Electricity use in buildings accounts for two-thirds of the demand increase by 2050.

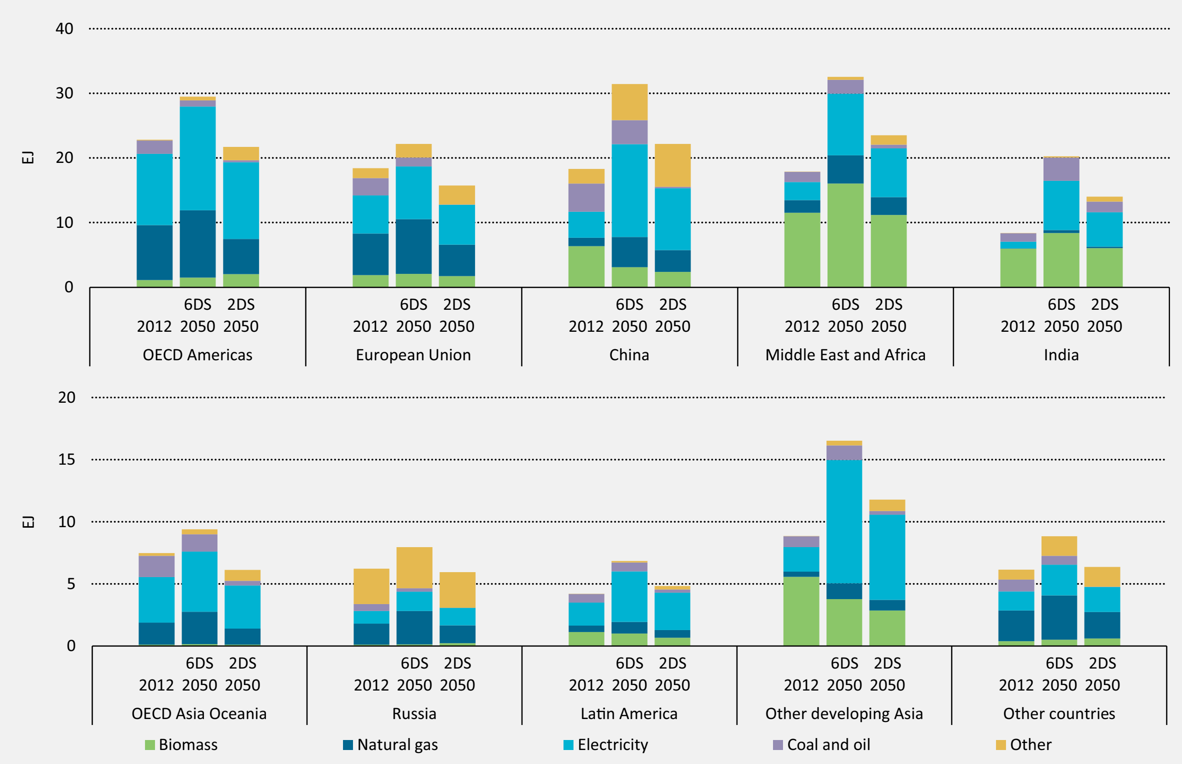
Effective action as part of the 2DS could limit global growth in buildings final energy demand to just 11% without changing comfort levels or requiring households to reduce their purchases and use of appliances and other electronic equipment. In many OECD countries, final energy consumption of buildings in the 2DS falls to below today's levels by 2050, while growth in emerging countries can be drastically curbed: India's growth, for example, is half of that compared with the 6DS and China's growth is two-thirds lower.

The share of fossil fuels in final energy demand for buildings, including the generation mix of electricity and heat in the power sector, falls to 30% in the 2DS in 2050, compared with around 60% in 2012. Decarbonisation of electricity plays a major role in this shift. The average global share of direct use of renewables stays at 30% in 2050 (similar to today's level), but the shares of individual renewable sources changes: whereas biomass currently accounts for almost all of the renewable energy use in the buildings sector, solar thermal energy gains a share of almost 10% by 2050 in the 2DS.

An estimated nearly 53 EJ, equivalent to current energy use for buildings in all OECD countries combined, could be saved in the buildings sector in 2050 in the 2DS compared with the 6DS, primarily through the wide deployment of advanced technologies and high-performance buildings (Figure 1.23). More efficient space heating is responsible for around one-quarter of these savings, while more efficient use of electricity in different services combined contributes almost 30% of the savings. The overall energy savings result in total direct and indirect emissions reductions of nearly 12 $GtCO_2$ in 2050, reducing the overall

CO_2 impact of the global buildings sector in the 2DS by 84% compared with the 6DS. Indirect emissions reduction, achieved by electricity savings and decarbonising electricity generation, is crucial in reducing the CO_2 impact of the buildings sector, accounting for almost 75% of the annual reductions in the 2DS in 2050 compared with the 6DS.

Figure 1.22 Buildings energy consumption by region



Note: "Other" includes solar thermal and geothermal energy.

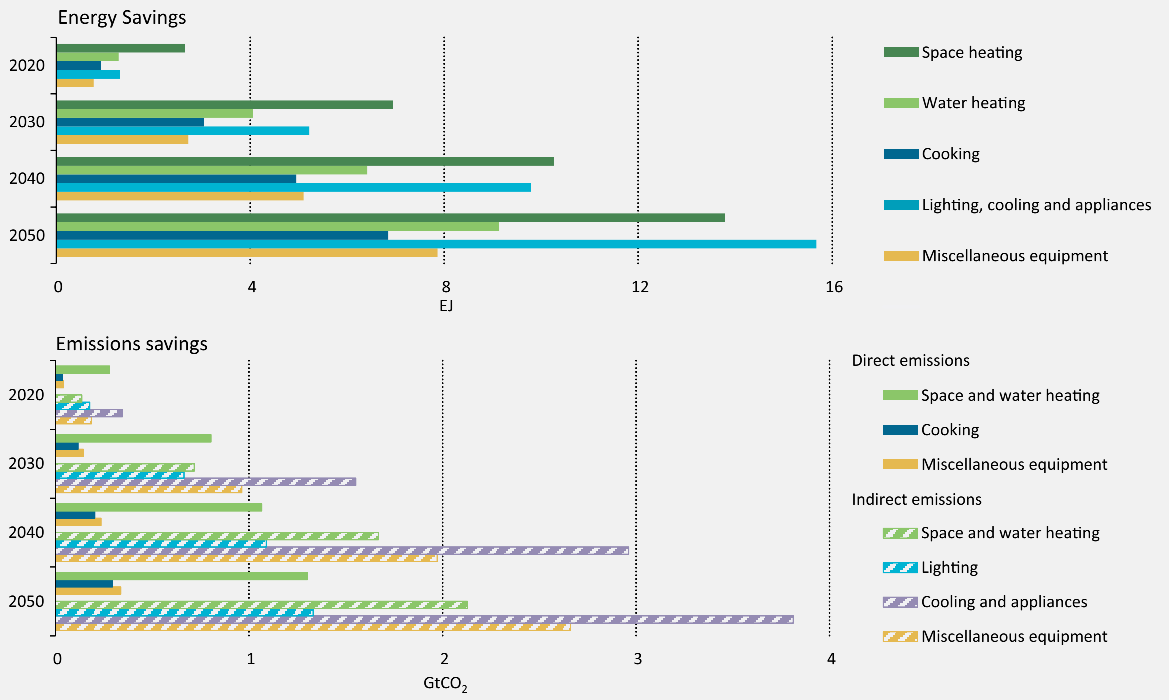
Key point *While fuel shares for the buildings sector vary around the world, the 2DS shows an increasing share of electricity, which covers (on average) more than 40% of global building energy needs in 2050 (compared with 29% in 2012).*

Key actions

Key policy actions in the buildings sector can stimulate widespread deployment of solutions. A systems approach that considers the whole building can facilitate synergies and result in capital cost savings. Within a systems approach, effective policy is also needed at the individual component level to ensure that all market opportunities are realised. Recommended actions are provided in *ETP 2014* and in *Transition to Sustainable Buildings: Strategies and Opportunities to 2050* (IEA, 2013a).

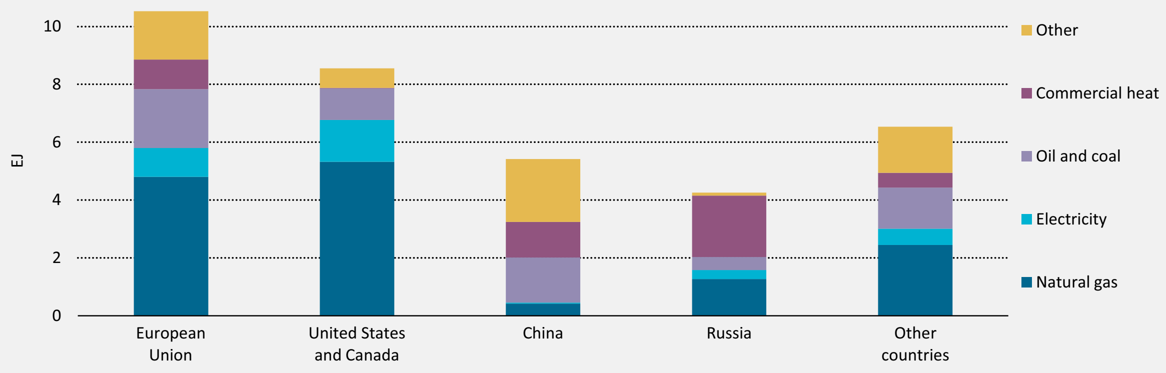
However, the largest end-use in buildings, heating for homes and businesses as well as for hot water, continues to be a critical area of special interest. While progress on new construction in mature cold climates has been significant, the existing building stock for the most part has been neglected. One region and four countries (the European Union, the United States and Canada, China, and Russia) account for the dominant part of global final energy consumed for space heating (Figure 1.24). Their challenges and policy options are therefore discussed in more detail.

Figure 1.23 Buildings final energy and emissions savings between 6DS and 2DS



Key point *Energy savings together with decarbonised electricity supply can reduce the CO_2 impact of the buildings sector by 12 $GtCO_2$ in 2050, or 84%, compared with the 6DS.*

Figure 1.24 Global space heating consumption and fuel shares in 2012



Note: "Other" includes solar thermal and geothermal energy.

Key point *One region and four countries – the European Union, the United States and Canada, China, and Russia – account for 80% of global energy use for space heating.*

The United States and Canada have made significant progress on reducing the heating load per unit of floor area, but with the size of homes continuing to increase, total consumption remains still high. Europe has recently built some of the most advanced buildings in the world with very low energy consumption, but is also saddled with a very large stock of old buildings that have not been refurbished to achieve deep energy reductions. China has been making progress with newly constructed buildings in the largest cities, but disseminating policies and ensuring compliance for all regions is a challenge. In addition, much of China's population is relatively poor and their desire for larger spaces and improved comfort will drive large growth in demand for heating. Russia's large natural gas resources result in low energy prices and inefficient heat use; although some progress has been made, the buildings sector has not matured at pace with global advances. While each region faces specific barriers, many opportunities exist to implement solutions to reduce heating energy demand (Table 1.1).

Table 1.1 Key elements to be considered to address the largest end use for heating in the world

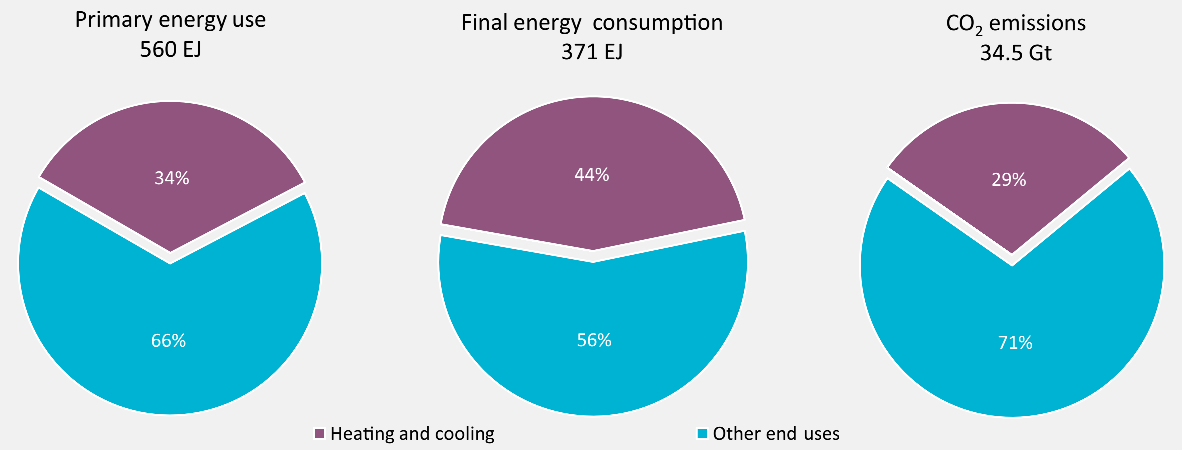
Key characteristic	European Union	United States and Canada	China	Russia
Recent trends	Stagnant overall progress, but new buildings and modest renovation offset modest population growth.	Declining demand due to improved buildings, better equipment, a declining stock of old buildings and population shift to warmer climates.	Robust growth in heating with population and income growth driving construction, along with fast-growing floor area per capita.	Declining demand with modern building construction and shift from old district heating systems to individual boilers.
Challenges	Policy strategies needed for existing stock; implementation is slow.	Heating per unit area has declined dramatically, but there is increasing demand for large spaces.	Large per capita floor area for current income levels.	Investment barriers due to high inflation and low energy prices.
Policy recommendations	Integrated policy packages needed for deep energy renovation and advanced components.	Vision for wide-scale, deep energy renovation and new approach for the existing market needed.	On track with building codes and equipment standards; greater focus on heat pumps and advanced district heating needed.	Shift from supply policy to improved energy efficiency policy essential; greater investment in advanced building materials and district heating systems.
Benefits	Reduced import gas dependency and resulting economic benefits.	Significant economic and energy savings, and economic stimulus.	Reduced coal demand, providing improved air quality.	Gas savings allowing larger gas exports; efficiency measures stimulate domestic manufacturing.

Significant energy savings in buildings can be achieved through the pursuit of deep energy renovations and very-low-energy new buildings, reflecting investments in advanced envelopes (highly insulating windows, optimal levels of insulation and air sealing), advanced electric and gas thermal heat pumps, solar thermal heating, and application of the most modern district heating networks. The 2DS pathway shows potential to achieve total world heating savings of at least 13 EJ by 2050 compared with the 6DS. The next section explores in more detail the role of heating and cooling in the global energy system, covering both buildings and industry.

Decarbonising the heating and cooling system

A major part of global energy use is linked to demand for heating and cooling in buildings and industry. Heating and cooling accounted in 2012 for 44% of global final energy consumption and 34% of primary energy (Figure 1.25).[7] Considering the indirect emissions linked to electricity and commercial heat generation, heating and cooling accounted for 30% of global CO_2 emissions in 2012. Despite the large scale of associated energy use and emissions, this area is often neglected in the discussion of decarbonising the energy system, which tends to focus on the electricity and transport sectors. The lack of explicit policy action on heating and cooling may reflect the complexity of the challenge: industry and buildings are very different contexts and the range of applications is huge, from individual water and space heating devices in homes to high-temperature furnaces in industry. Thus, unlike electricity, heating and cooling do not neatly represent a uniform product, and it is necessary to differentiate its demand categories by temperature levels to identify suitable low-carbon technology options.

Figure 1.25 Primary and final energy use for heating and cooling, and related CO_2 emissions in 2012



Key point *Heating and cooling in industry and buildings accounts for more than 40% of final energy consumption and 30% of global CO_2 emissions.*

Final energy consumption for heating and cooling

Heating and cooling consumed around 160 EJ of final energy in 2012, with a roughly equal split between buildings (52%) and industry (48%). Temperature is a key difference across the two sectors: heat services in the buildings sector require largely low-grade heat at temperatures below 100°C while industrial heat services are dominated by heat demands above 100°C. Around two-thirds of industrial final energy demand is for heat in the range of 200°C to 400°C.

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[7] On a primary energy basis, including the conversion losses in electricity and commercial heat generation, the primary energy share is lower than the final one, since other end-use services involving electricity entail higher conversion losses of primary energy. But heating and cooling combined still are estimated to be responsible for the largest share of primary energy use compared with other individual end-use services (mobility, motors in industry, appliances, etc.).

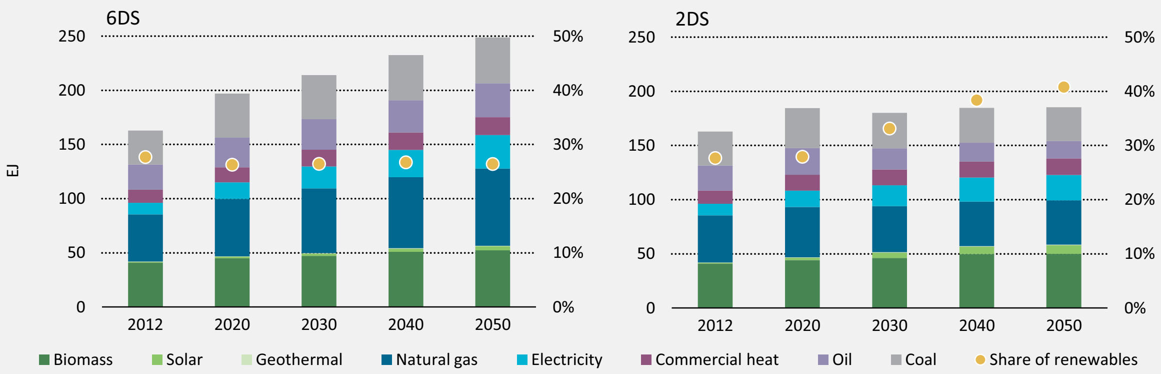
Overall, industrial final energy consumption for heating and cooling accounted for more than half of the final energy consumption in industry in 2012. Non-energy-intensive industry sectors (such as food and tobacco) combined were responsible for almost 40% of industrial heat demand, while consumption by individual energy-intensive sectors was diverse. Iron and steel accounted for one-third of total heat demand; chemicals and non-metallic minerals each consumed a share of 13%.

Heating services in the buildings sectors (e.g. space heating, warm water and cooking) were responsible for almost three-quarters of the sector's final energy consumption in 2012. Space heating dominates with a share of 42%, followed by water heating (26%) and cooking (26%), and only 7% for cooling. The relatively large share of cooking is caused by the use of traditional biomass (often in combination for water heating) with low conversion efficiencies in developing countries.

Looking at the energy mix, around 70% of the final energy consumption for heating and cooling today is based on fossil fuels. This figure takes into account the generation mixes for electricity used for heating and cooling, and for commercial heat. Renewables account for the remaining 30%, of which almost 90% is the traditional biomass use mentioned above.

In the 6DS, the share of fossil fuel use for heating and cooling stays around 70%. It would need to fall below 50% by 2050 to meet 2DS objectives, with renewables accounting for 41% of the final energy consumption and around 10% linked to renewable generation of electricity and commercial heat (Figure 1.26). In the residential sector, for instance, the use of heat pumps for space heating reaches a global average of around 20% of the useful space heating demand. Solar energy accounts today for less than 1% of final energy for heating purposes in buildings. With solar water heating systems becoming a mature technology that is cost-competitive with heat from fossil sources in many countries, solar energy is poised to play a stronger role. Under the 2DS, solar heating reaches global average share of 10% by 2050 in the buildings sector, mainly driven by residential water heating as solar thermal collectors reach a share of 17% (Box 1.6). Biomass remains an important source for heating in the 2DS, but its use by sector changes: traditional biomass use in the residential sector declines, whereas industry use of biomass (mainly in solid form) for heating triples between 2012 and 2050.

Figure 1.26 Global final energy consumption for heating and cooling



Key point *Final energy consumption for heating and cooling can be curbed in the 2DS almost at today's levels, with more than two-fifths of the energy use provided by renewable sources in 2050.*

Box 1.6 Recent trends for solar heating and cooling

Solar heating and cooling (SHC) can provide low-carbon energy for a range of services such as domestic water and space heating, space heating for large-scale industrial heat applications, and solar thermally driven cooling systems.

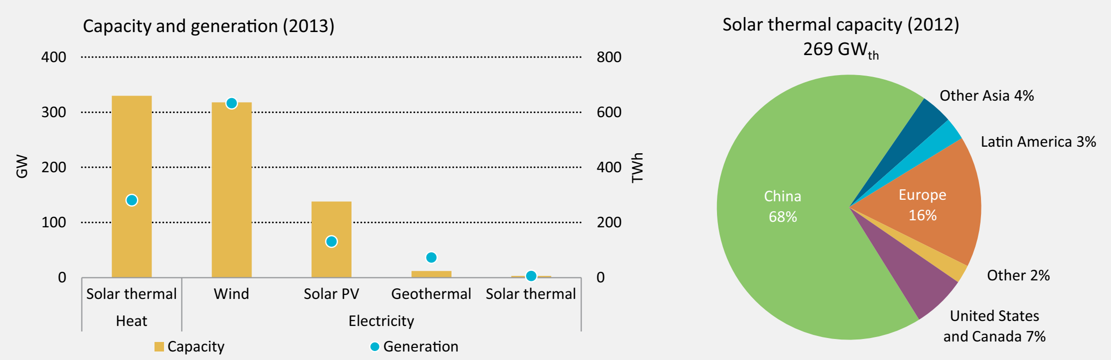
By the end of 2012, solar thermal systems with a thermal capacity of 269 gigawatts thermal (GW_{th}) were installed worldwide, corresponding to 384.7 million square metres (m^2) of collector area and delivering annual heat generation of 228 TWh. The vast majority (83%) of this capacity was installed in China (180.4 GW_{th}) and Europe (42.8 GW_{th}). This amount of low-carbon energy translates into CO_2 savings of 79 $MtCO_2$, or 3% of annual CO_2 emissions of the global buildings sector in 2012. First statistics for 2013 indicate continued rapid growth, with an estimated total capacity of 330 GW_{th} by the year's end.

Apart from the very large contributions from the "traditional" renewables of biomass and hydropower, solar heating's contribution in meeting global energy demand is second only to wind power (Figure 1.27).

The number of solar thermal systems in operation in 2012 was approximately 78 million, with 78% used for domestic hot water preparation in single family houses, 9% attached to larger hot water consumers (e.g. multi-family houses, hotels, hospitals, schools, etc.) and 8% for swimming pool heating. Around 4% of installed capacity supplied heat for both domestic hot water and space heating (solar combi-systems). The remaining systems (about 1% or almost 4 million m^2) delivered heat to district heating networks, industrial processes or thermally driven solar cooling and air-conditioning applications.

Megawatt-scale solar-supported district heating systems, as well as SHC applications in the commercial and industrial sectors, have attracted increased interest, particularly with the recent launch of several ambitious projects. In June 2013, the world´s largest collector field was commissioned in Chile; the installation covers 39 300 m^2 of flat plate collector area connected to 4 000 cubic metres (m^3) of thermal energy storage for a maximum thermal peak capacity of 32 megawatts. The projected annual thermal energy output of 51.8 gigawatt hours is designed to cover 85% of the process heat demand needed to refine copper at the world´s largest copper mine.

Figure 1.27 Solar thermal heating in comparison with renewable electricity and regional breakdown of capacity



Note: "Europe" includes the European Union, Albania, Former Yugoslav Republic of Macedonia, Norway, Switzerland, Russia and Turkey.

Key point *Compared to renewable electricity generation, solar thermal heating ranks second after wind (when excluding biomass and hydropower), with deployment being driven by China.*

The world's largest solar district heating plant began operation in February 2014 in Dronninglund, Denmark. With a transparent collector area of 37 275 m^2 (26 megawatts thermal capacity) and a 60 000 m^3 seasonal pit heat storage, the collector is designed to cover around 50% of the total annual heat demand of 1 400 connected customers. The plant also includes gas motors for co-generation of electricity and heat, an absorption heat pump, a biomass boiler and a backup oil boiler. Due to the large heat storage, the gas motors will always be able to produce electricity when prices are high – even when there is no heat load (as the storage can then take the heat production). More so-called "smart" district heating plants with large-scale solar thermal systems and seasonal storage are scheduled to be built in Denmark.

Source: Mauthner, F. and W. Weiss (2014), *Solar Heat Worldwide: Markets and Contribution to the Energy Supply 2012*, IEA Solar Heating and Cooling Programme.

Energy efficiency also plays a major role in decarbonising the heating and cooling demand by reducing final energy consumption in both buildings and industry by around 30% in 2050 in the 2DS compared with the 6DS. In the buildings sector, for example, improving the building envelopes of both existing and new-built stock can provide significant energy savings: in 2050, such measures deliver annual savings of 6 EJ for residential buildings and 1.5 EJ in services buildings, almost 15% of overall energy savings in the buildings sector.

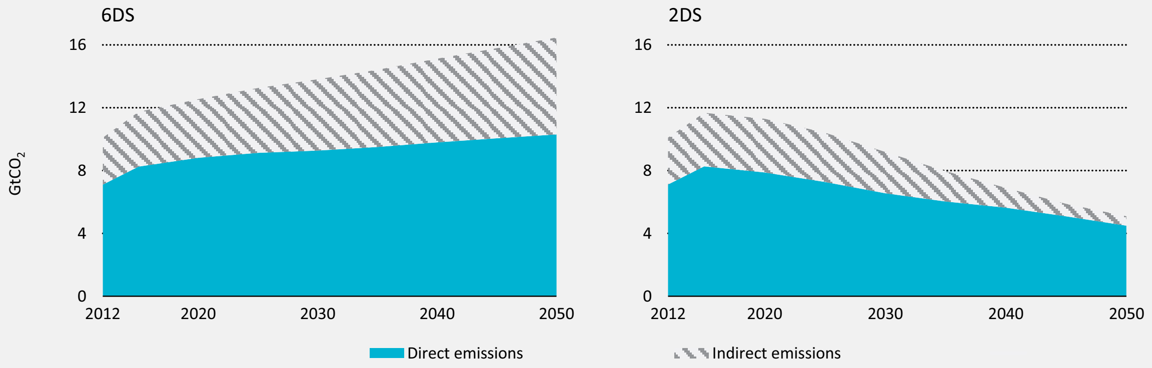
In industry, energy efficiency is important in two respects: to reduce the energy requirements in production processes (e.g. steam use in a chemical reactor), but also to improve the energy efficiency of on-site services used in such processes (such as steam). Both components combined reduce industrial energy needs for heating by one-third in 2050 in the 2DS relative to the 6DS. Reusing waste heat (which would otherwise be ejected into the environment) from industrial processes or power plants is another option to increase overall efficiency of heat systems in industry and in district heating of buildings. Low-temperature waste heat may also be used to cover local cooling needs through absorption chillers. Electricity can also be generated from waste heat in organic Rankine cycle plants, which use working fluids with lower boiling temperatures (80°C to 350°C) than are used in conventional steam cycle plants.

The potential of waste heat acquired through these technical options is huge, but its realisation hinges on local conditions. Heat cascading, which uses waste heat from high-temperature industrial processes in other industries with low-temperature heat demand or for district heating, depends on the proximity of industrial production sites with compatible heat temperature levels or of a district heating grid. Local assessments, in the form of heat mapping, are needed and must take into account potential heat sources and sinks to explore the technical and economic potential for reuse of waste heat.

CO_2 emissions

Widespread deployment of innovative technologies and improved efficiency in the 2DS deliver emissions reduction from heating and cooling of 50% by 2050 in the 2DS compared with today. Reductions in indirect emissions are crucial, providing around 49% of the annual CO_2 savings in 2050 (Figure 1.28). This stresses the need to develop integrated strategies that optimise both the heat and cooling applications in buildings and industry and the upstream electricity and heat generation sector, as discussed in the following section.

Figure 1.28 Direct and indirect CO_2 emissions from heating and cooling in the 6DS and 2DS



Key point *In the 6DS, direct and indirect CO_2 emissions from heating and cooling continue to grow over time; by contrast, they peak by 2015 in the 2DS and decline substantially thereafter.*

Linking heat and electricity systems

Transforming heating and cooling systems cannot be pursued in isolation from the rest of the energy system, especially the electricity system. Synergistic opportunities exist that could deliver solutions for the energy transition. Co-generation plants, which produce both electricity and heat for use in district heating or process heat for industrial use, are already capitalising on the links to simultaneously improve overall energy efficiency for generating electricity and cover heat (or cooling) needs.

Decarbonisation of electricity in the 2DS is based on aggressive efforts in many parts of the world to boost electricity generation from variable renewable sources (notably solar PV and wind), increase use of low-carbon electricity in the end-use sectors, and optimise flexibility needs in the electricity system. Analysis shows that the electricity system could benefit from the flexibility provided by creating larger, integrated electricity and heat systems. Different measures exist to achieve this, some of which are already used today.

Co-generation can be designed, or in case of existing plants modified, to operate more flexibly. Typically, operation of co-generation plants is driven by heat demand (either for district heating or industrial production processes), which often limits the flexibility they can provide to the electricity system (Box 1.7). Adding an auxiliary heat boiler can increase flexibility by allowing co-generation plants to be ramped down when electricity demand is low while still covering the heating needs.

Thermal storage is another measure to increase the operational flexibility of a co-generation plant. The plant can be operated with higher priority to electricity generation with surplus heat diverted into thermal storage (e.g. when the co-generation plant is ramped up to compensate for lack of wind generation), where it remains available for discharge on demand (e.g. when the co-generation plant is ramped down in times of excess wind generation). Converting surplus electricity through large-scale heat pumps or electric furnaces into heat (so-called "power-to-heat") is another option either for direct use or to charge thermal storage for later use.

The potential for these flexibility options, however, depends on the overall potential and economics of co-generation to provide these heat services in the industry or buildings sectors in competition with other heating technologies.

Box 1.7 Flexibility of co-generation plants

New thermal power plants generating only electricity currently achieve conversion efficiencies ranging from 42% for open-cycle gas turbines (OCGT) to over 47% for steam cycles (SC), 50% for ICEs and 60% for combined-cycle gas turbines (CCGT). The portion of the fuel input not converted into electricity is lost as waste heat to the environment. Co-generation plants use part of this waste heat to deliver heat to buildings or industry, thus reaching overall fuel conversion efficiencies of up to 90% or higher.

In many applications, a co-generation plant operation follows a given heat demand. Without additional equipment (e.g. auxiliary boilers or thermal storage), this operational approach restricts the flexibility that a co-generation plant can provide to the electricity system, as electricity and heat output are not completely independent from each other, but linked depending on the technology type and its design. The degree to which electricity and heat output can be decoupled varies among SC, OCGT, CCGT and ICE co-generation plants.

Two types of SC co-generation plants exist: *backpressure* and *extraction-condensing plants*. In backpressure plants, steam in the steam turbine is not relaxed down to the level of a condensing power plant, but leaves the turbine at a higher pressure and temperature level, so that it can be used for heating purposes. Such plants are characterised by a fixed ratio of electricity and heat output. Some flexibility can be achieved in the design by adding a separate low-pressure turbine. If heat demand is low (e.g. in summer in a district heating application), the heat from the backpressure turbine can be used to generate additional electricity. Extraction-condensing co-generation plants allow a flexible extraction of steam for heating purposes between the different turbine stages. The steam fraction not used for heating is fed into the condensing stage of the turbine for electricity generation. Extraction-condensing plants can be run flexibly between a pure condensing mode that generates only electricity and a backpressure mode that uses less steam for electricity generation to maximise heat output (or vice versa; heat output can be reduced to ramp up electricity output).

The flue gas of a gas turbine has a sufficiently high temperature (500°C to 600°C) so that it can be used to generate hot water or steam in a waste heat recovery boiler in an *OCGT co-generation plant*. OCGTs in combination with a boiler have become particularly popular for industrial applications for several reasons, such as relatively low costs and space requirements, modular size, and flexible operation in terms of start-up time, ramp-up/-down rates, etc. OCGT co-generation plants can be run in pure electricity mode, but compared with an extraction-condensing SC plant, the additional electricity output gained by not producing heat is rather small.*

Different designs exist for *CCGT co-generation plants*. Part of the flue gas of the gas turbine can be used for heating purposes (similar to an OCGT), but in many designs this flue gas is used exclusively to generate steam for an extraction-condensing steam turbine, which then allows a flexible heat extraction.

ICE co-generation plants use a principle similar to that of OCGT, using the flue gas in a waste heat recovery boiler to generate hot water or steam. The cooling water from the engine provides an additional heat source; in contrast to the flue gas, however, it has a much lower temperature (around 90°C) that is not suitable for industrial process heat applications. As for OCGTs, reduced heat generation does not result in a significant increase in electricity output.

* In heat generation mode, diverting the flue gas through the heat recovery boiler is accompanied by a pressure drop, resulting in a higher turbine exit pressure and thus slightly lower power output compared to the operation mode, when the OCGT only generates electricity.

Electricity can also be used directly for heating and cooling in buildings and industry. Electric water heaters combined with storage tanks can provide flexibility to the electricity system. This approach is being used already today; in France, for example, more than 13 million storage tanks are charged during night hours to maximise use of electricity generated by nuclear power plants. Using hot water pumps instead of direct electric heaters can improve the overall efficiency of water heating with electricity. Heat pumps for space heating can also provide flexibility to the electricity system; by using the mass of the building as thermal storage, operation of the heat pump can be shifted by a few hours, thereby avoiding its use during peak-load hours.

To realise the advantages of electrification of the heating system, planning of the linked electricity and heat system has to take into account and address possible risks of an electrification strategy on a larger scale. One example is the spike in electricity demand for heating during extreme cold winter days or, in hot climates, similar electricity consumption peaks in summer due to increased air conditioner use.

Widespread deployment of efficient heating and cooling technologies depends on several factors. The technical and economic aspects of the heat and electricity system are fundamental, but often face regulatory, policy and finance barriers or risks. The IEA CHP (Combined Heat and Power) and DHC (District Heating and Cooling) Collaborative used case studies of successful co-generation and DHC projects to analyse strategies to address these barriers. It identified a long-term, stable market environment that rewards energy efficiency as important to reducing investment risk (IEA, 2014d). Strategic planning to link local, regional and national heating and cooling planning – in part by mapping source and demand points – is also crucial to identify cost-effective opportunities to develop new co-generation or refurbish existing infrastructure. With a focus on urban energy systems, *ETP 2016* will further analyse the role urban co-generation and district heating systems can play in meeting local energy needs while also providing flexibility to local and national electricity grids.

Investment needs and fuel cost savings

According to *ETP 2015* analysis, transition to low-carbon systems for the buildings, industry, transport and power generation sectors will require substantial investments between today and 2050. For this analysis, the investment costs have been defined as follows in the four sectors:

- Buildings investments include heating and cooling, other end-use technologies, and energy-efficient building envelope (insulation, windows, roofs and seals).
- Industry covers investments in the iron and steel, chemicals, cement, pulp and paper, and aluminium sectors, but not non-energy-intensive sectors.
- Transport includes the investments for the transport modes road, rail, shipping and aviation for passenger and freight transport.
- Power sector investments comprise generation technologies for electricity (and heat) as well as transmission and distribution.

In contrast to the IEA *World Energy Investment Outlook 2014* (IEA, 2014c), *ETP 2015* investment analysis does not cover upstream investments in fossil fuel and biomass production, or in their transport infrastructure. These are implicitly included in the following analysis of fuel cost savings, which uses primary fuel prices to assess (between scenarios) how changes in primary energy use affect costs on the import and export bills of countries.

These primary fuel cost savings are not comparable with savings in consumer expenditures for final energy.

Based on the outlined approach, the 2DS estimates the need for absolute investments of around USD 359 trillion between 2016 and 2050. This is about USD 40 trillion (13%) more than for the 6DS (Table 1.2).[8, 9] Compared to *ETP 2014*, the estimate of the additional investment requirements is 10% lower, mainly due to a revision of the investment cost assumptions for non-road transport modes, namely shipping and aviation. The additional investment may appear huge, but represents less than 1% of the cumulative global GDP in purchasing power parity terms over the same period.[10] Almost half, USD 19 trillion, of the additional investment is needed in the transport sector, with the larger portion required post-2035 to support the large-scale roll-out of EVs. Additional investment needs in the buildings sector, of around USD 11 trillion, are driven by deep renovation of the buildings stock and investments in more energy efficient appliances. In the power sector, additional investment needs in low-carbon technologies, around USD 14 trillion, are offset by reduced investments (USD 5 trillion less) in unabated coal and gas plants (bringing net investments to USD 9 trillion). The additional investments of USD 1.2 trillion in the industry sector are driven by roll-out of energy efficiency and fuel-switching measures and deployment of CCS.

Table 1.2 Investment requirements by sector, 2016-50

USD trillion	Absolute investments		Additional investments, 2DS	Average annual investments	
	6DS	2DS	2DS minus 6DS	6DS	2DS
Buildings	17.0	28.2	11.2	0.5	0.8
Industry	8.9	10.1	1.2	0.2	0.3
Transport	265.7	284.3	18.6	7.6	8.1
Power	26.8	36.1	9.3	0.8	1.0
Total	**318.4**	**358.8**	**40.4**	**9.1**	**10.3**

Notes: The reporting period for the investment costs has been adjusted from 2011-50 in *ETP 2014* to 2016-50 in this analysis, so that the absolute investments reflect only future investment needs, excluding any historic investments. This explains why the absolute investment numbers shown in this table for the 6DS and 2DS are for buildings, industry and transport lower than in *ETP 2014*. The absolute investment numbers for transport shown here are higher than in *ETP 2014* due to a change in the methodology: the investment numbers for PLDVs now include the total vehicle costs, whereas *ETP 2014* only took into account the costs of the powertrain for PLDVs.

The major portion of the additional investments in the energy sector needs to be directed to OECD non-member economies, reflecting strong demand growth in emerging and developing countries. In the power sector, 54% of the additional investments accrue to these regions; in transport, they require 60% of the investments (Figure 1.29).

Importantly, outcomes of the 2DS more than offset the additional investments required compared with the 6DS, with less spending on fossil fuels being a major factor. The 2DS fuel cost savings are estimated to be around USD 115 trillion for 2016-50, a large part of which reflects dramatically lower oil consumption in transport and industry. Cumulative energy savings for coal between the 2DS and the 6DS are actually higher in energy terms, but less economically important because of coal's much lower price. Taking into account the undiscounted fuel cost savings, the 2DS results in net savings of around USD 75 trillion compared with the 6DS (Figure 1.30).

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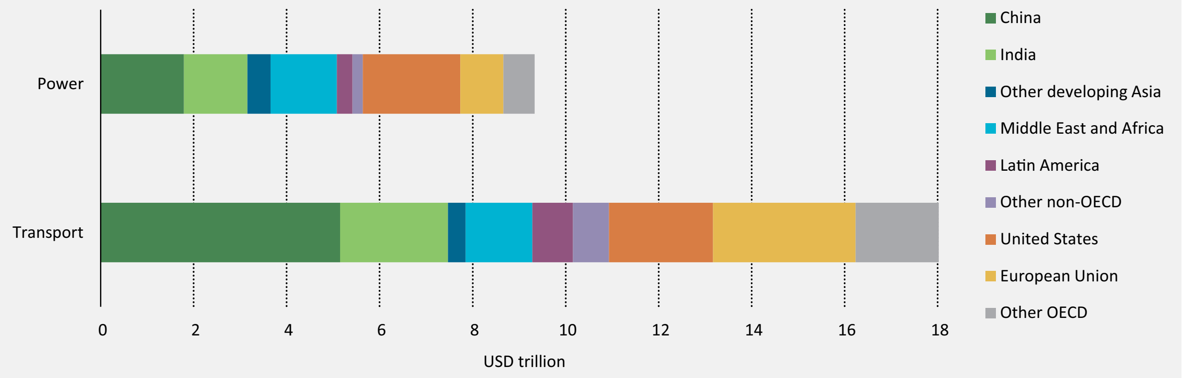
[8] Unless otherwise stated, all costs and prices are in real 2013 USD, i.e. excluding inflation.

[9] Cumulative investment numbers are undiscounted. The impact of discounting at rates of 3% and 10% is illustrated in Figure 1.30.

[10] The comparison to GDP number should illustrate only the size of the investment needs. ETP analysis does not assess the economy-wide impacts of the 2DS, such as on GDP, but focuses only on developments in the energy sector.

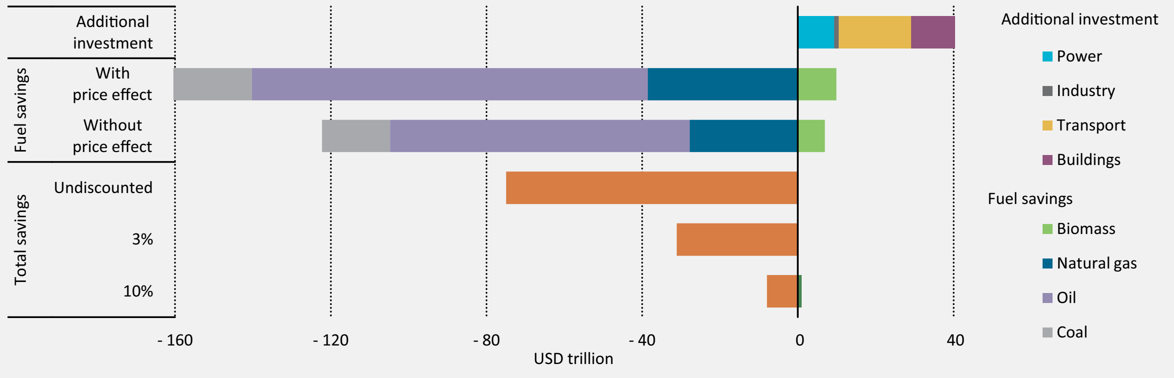
Figure 1.29 Additional investment needs in power and transport for the 2DS (relative to the 6DS), 2016-50



Key point *OECD non-member economies dominate the additional investment needs in power and transportation in the 2DS.*

Discounting the future investment needs and fuel cost savings lowers the net savings to USD 31 trillion (discount rate of 3%) or USD 8 trillion (10% discount), but still yields net benefits. Other factors that are uncertain could alter the analysis of net savings, especially the evolution of future fuel prices used to estimate the fuel cost savings. Despite the inherent uncertainties in valuing the future fossil fuel savings, the huge reductions in fossil fuel consumption (with cumulative primary oil consumption in the 2DS being one-third lower than in the 6DS and cumulative coal consumption halved) and the related cost benefits could help to fund the needed investments in low-carbon technologies in the 2DS.

Figure 1.30 Additional investments and fuel savings in the 2DS (relative to the 6DS), 2016-50



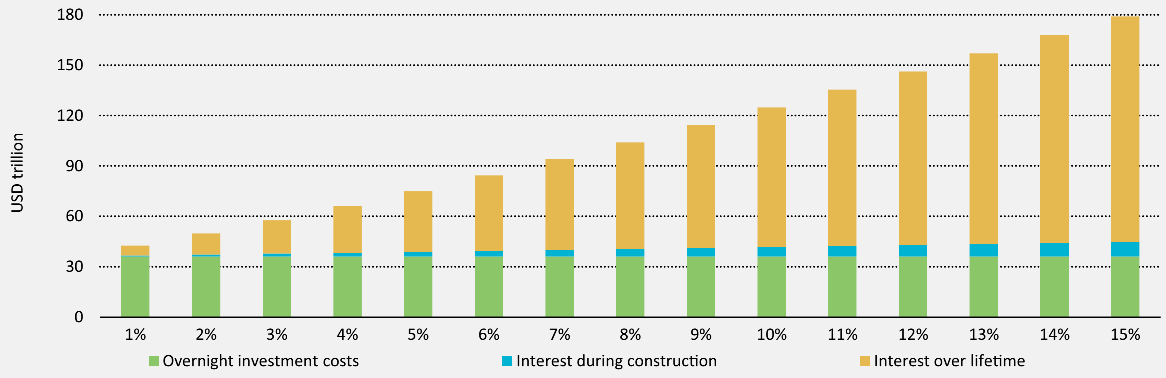
Key point *Additional investment needs of USD 40 trillion in the 2DS are more than offset by savings of USD 116 trillion in fuel cost expenditures.*

Financing costs are not included in the investment cost numbers in Table 1.2; the cost of capital can, however, have a profound impact on overall costs as illustrated by showing the power sector investment in the 2DS for different cost of capital rates (Figure 1.31). At a cost of capital of 8%, the rate *ETP* uses in the scenario analysis for the power sector, financing costs are almost twice the original overnight investment costs.[11] The major part of the financing costs accrues over the economic lifetime of the power plants and is to be covered by the operating revenues. Obviously, the higher the costs of capital, the higher the revenues needed.

The second component of financing costs, the interest during construction (IDC) of a plant, is much smaller but still noteworthy. For the power sector investments in the 2DS (at the same 8% cost of capital), the IDC corresponds to 13% of the overnight investment costs. As IDC has to be paid during construction – i.e. at a time with no operating revenues – it typically drives up the total initial capital required for a project.

Policies should aim to ensure stable and predictable market conditions to avoid unnecessary risks that result in higher cost of capital. In regions where access to capital is difficult, governments can intervene by absorbing some of the risks (e.g. by providing loans or guarantees), though the long-term goal should be to establish a stable market setting that supports a functioning finance system.

Figure 1.31 Impact of cost of capital on financing costs in the power sector for the 2DS



Key point *Interest paid over the lifetime of a plant accounts for the major part of the financing costs, while interest payments during construction time are smaller, but have to be paid before a plant starts operating.*

Policy action to lead the transition

Comprehensive policies that mobilise swift actions across the entire energy system, involving stakeholders from government, industry and research as well as the public, are required to shift the current, largely unsustainable, trends of the global energy system onto a sustainable pathway towards the 2DS.

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[11] Overnight investment costs include owner's cost; engineering, procurement and construction; and contingency, but exclude IDC. Financing costs represent IDC and interest costs paid over the economic lifetime of a plant.

Energy prices should reflect the true costs of energy to stimulate the deployment of low-carbon technologies. Carbon pricing, through instruments such as carbon taxes or emissions trading schemes, is one important component to achieve a low-carbon energy future. At the same time, fossil fuel subsidies, which lead to inefficient use of energy, should be phased out. With USD 550 billion in 2013, total fossil fuel subsidies exceeded the subsidies for renewables by a factor of four (IEA, 2014e). Carbon pricing and removal of fossil fuel subsidies on their own, however, will not deliver the 2DS objectives; they need to be complemented by a broader range of policy instruments (e.g. standards and codes for buildings or vehicles) to address other barriers not influenced by price.

Policy design is a further fundamental aspect of an effective low-carbon pathway: policy instruments should be stable and predictable to foster investments in the often capital-intensive low-carbon technologies, while being flexible enough to adapt to technology developments or changes in economic conditions. Uncertainty regarding future policy regulation undermines investor confidence and further increases investor risks, which translates into higher costs of capital. Governments can also actively address investment risks through instruments that reduce financing costs, such as lending from national development banks, loan guarantees or publicly backed green bonds.

To develop national policy goals and the instruments to achieve these targets, a holistic view of the energy system is needed, considering the interdependencies among energy sectors and technologies and to ensure consistency in policy making. Energy systems modelling and analysis are effective tools to set appropriate national goals and develop effective strategies. Countries should regularly check progress towards their set goals, in order to adapt policy instruments accordingly. An indicator framework to track progress, as discussed in the following chapter, "Tracking Clean Energy Progress", is a useful tool to benchmark current developments and trends against policy targets.

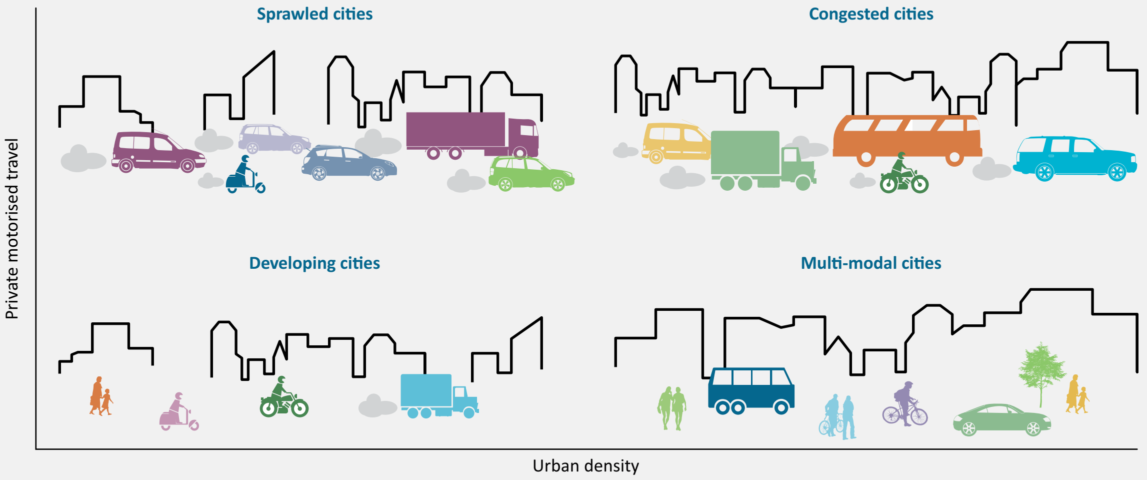
Policy action has to take into account the maturity and development status of the different energy technologies. Near-term action on already mature low-carbon technologies, such as end-use energy efficiency, can help to provide time to further develop and demonstrate other low-carbon technologies and infrastructure needed to fully decarbonise the energy system in the long term. This does not mean that current policies should focus only on those areas providing near-term results, but should maintain also a long-term view by pushing new technologies into market viability, with sustained efforts in RD&D. Aspects related to how technology policy has to address technology innovation are discussed in more depth and illustrated in Part 2 of this book.

A further dimension in the transition to a sustainable energy system is the level where policy action needs to happen. Given that urban areas are already home to more than half of the world's population and account for two-thirds of final global energy consumption, cities and local policies will have a major impact on the sustainability of the future global energy system.

By 2050, the urban population will climb to as many as 6.3 billion people (two-thirds of the global population); the consequent urban energy demand growth will have important implications for long-term economic development, energy security and environmental sustainability. At present, the role urban energy systems could play in achieving energy and climate targets is poorly understood, particularly as urbanisation is evolving rapidly and along diverse paths.

Cities around the world differ, ranging in size from a few thousand inhabitants to megacities with multimillion populations. Other factors, such as urban form, density, expected population and economic growth, will determine the needs for housing, water, energy and mobility – as well as the strategies required to address such needs. Sprawled urban areas, characterised by a low population density, often result in higher transport demand; when this demand is covered by private transport, it leads to higher per capita energy demand than in a more compact city with favourable conditions for public transport (Figure 1.32). The ways in which city policies align with national policy ambitions, and vice versa, will become increasingly important as time goes by.

Figure 1.32 The impact of city typologies on motorised private travel



Source: IEA (2013b), *A Tale of Renewed Cities*, Policy Pathway, OECD/IEA, Paris.

Key point *Various factors, such as urban form, density and economic growth, affect travel demand and transport solutions.*

Policy actions designed to shape patterns of urban energy use could reduce by at least one-quarter the projected increase in global urban energy demand in 2050, with actions targeting energy efficiency and fuel switching being most important (GEA, 2012). The emerging role of distributed generation in urban areas, coupled with greater integration of energy infrastructures (e.g. linking power and heat systems), could boost the complementary capacity of demand-side measures.

Policy makers at national and local levels have different objectives and responsibilities, and different instruments available to influence the development of urban energy systems. The potential risk is that if both policy realms are not well aligned, cities will bear the burden of increasing inefficiencies and costs. Local policies often have a strong influence on local infrastructure development (e.g. through city-owned utilities) and demand (e.g. land-use planning), but may not match national policies, which are traditionally more oriented towards supply but can also impact demand (e.g. through energy taxation).

These challenges have prompted *ETP* to focus the 2016 edition on energy systems in cities, seeking to identify how local energy policies and their interplay with national initiatives can make cities more efficient, secure and sustainable while also contributing to national and global energy policy objectives. The analysis will examine interactions among different components of urban energy systems, including how energy technology and policy responses can keep pace with growing urban energy demand.

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Chapter 2

Tracking Clean Energy Progress

Market viability of some clean energy technologies is progressing, but the overall rate of deployment falls short of achieving the 2°C Scenario (2DS). Strong actions linked to stated targets need to be pushed forward to achieve clean energy potential and to avoid escalating future costs of decarbonisation.

Key findings

- ***The cost gap between electricity generated from renewables and that from fossil fuels is narrowing.*** *Some renewables are already competitive with new-built fossil fuel plants in various locations. In addition, long-term contracts with record-low prices were signed for both onshore wind and utility-scale solar photovoltaic (PV) projects over the last year showing the significant improvement on the cost of energy for some renewables.*

- ***Low-priced coal was the fastest-growing fossil fuel in 2013, and generation increased in all regions.*** *Newer coal plants can perform to a relatively high standard. But where capacity is expanding, in emerging economies for example, less efficient, subcritical units dominate.*

- ***A significant milestone for carbon capture and storage (CCS) was reached with the opening of the first commercial-scale coal-fired power plant (CFPP) with carbon dioxide (CO_2) capture in October 2014.*** *Progress overall, however, is slower than required to meet the 2DS targets.*

- ***Buildings energy demand continues to grow rapidly; in fact, the growth rate would need to be halved to achieve 2DS targets, meaning that each year, the gap grows larger.*** *While there are more examples of large-scale successful measures, energy efficiency renovations need to scale up as buildings' energy demand continues to grow largely unabated.*

- ***In energy-intensive industries, deployment of best available technologies (BATs) and energy-saving measures and demonstration of innovative low-carbon processes have been relatively slow over the last decade and need to accelerate to match stated ambitions.*** *Finding new pathways for public-private collaboration and co-operation, as well as more effective support mechanisms, will be critical to meeting short-term milestones and climate targets through 2025.*

- ***Reframing climate goals through energy metrics can help highlight various drivers for low-carbon technology deployment, and support ambitious, yet realistic, targets.*** *International climate agreements have traditionally focused on greenhouse gas (GHG) emissions and measures, but alternative metrics that can be framed around energy efficiency, new investment in clean power generation, and even advances in research, development and deployment (RD&D) can help to identify opportunities for actions with long-term as well as short-term impacts.*

Opportunities for policy action

- *Electricity prices need to reflect the true environmental costs of generation, and market frameworks should adapt to the increased production of variable and distributed clean energy generation. The introduction of strong market incentives such as carbon pricing is required to make low-carbon sources competitive in an era of continuing low coal prices.*
- *Policy uncertainty is the main barrier to deploying renewables. Policy should focus on cost efficiency to prevent over-remuneration of some technologies, but policy changes must be predictable and retroactive changes avoided at all times.*
- *Countries beginning to deploy variable power plants should implement well-established best practices to avoid integration challenges. Smart grids can provide enhanced monitoring, control and directionality to grid operators while the deployment of energy storage can provide additional flexibility of the electricity system. Market regulation can strongly support the uptake of system integration technologies.*
- *Fuel efficiency standards have proven to be an effective method for improving vehicle fleet efficiency; expanding the application of these standards beyond PLDVs is now necessary. Also, as the PLDV market in non-member economies of the Organisation for Economic Co-operation and Development (OECD) is now bigger than the OECD market and continuing to grow, policy measures to improve fuel economy of new PLDVs need to be further introduced in OECD non-member economies.*
- *Energy sector decarbonisation needs to be tracked, with electricity decarbonisation of particular importance. Tracking both technology- and sector-specific indicators is useful to get a clear picture of opportunities and bottlenecks in decarbonising the energy system as a whole.*
- *Establishing and maintaining sound policies requires the availability of good quality, timely, comparable and detailed data and indicators. Promoting the development of indicators for evaluating penetration, costs and benefits requires both national data collection and international data co-ordination.*

Tracking Progress: How and against what?

Tracking Clean Energy Progress (TCEP) examines whether current policy is effectively driving efforts to achieve a more sustainable and secure global energy system. 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, while also demonstrating the potential to save energy and reduce emissions.

TCEP uses interim 2025 benchmarks set out in the 2DS, as modelled in *Energy Technology Perspectives 2015* (*ETP 2015*), to assess whether technologies, energy savings and emissions reduction measures are on track to achieve the 2DS 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.

The chapter is divided into 19 technology or sector sections, and uses graphical overviews[1] to summarise the data behind the key findings. This year’s edition contains a special feature on metrics to support national action on energy sector decarbonisation, which is particularly relevant given that a new agreement will be negotiated in 2015 under the United Nations Framework Convention on Climate Change (UNFCCC).

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[1] Enhanced interactive data visualisations are available at: www.iea.org/etp/tracking.

***TCEP* focuses on whether the actions needed to decarbonise the energy sector over the ten years to 2025 are progressing.** It also uncovers areas that need additional stimulus. *TCEP 2015* introduces a second qualitative evaluation of progress, which reflects whether the rate of technology deployment, cost reductions, policy changes and other necessary measures have been positive, negative or limited. This evaluation is based on progress or activity in the last year or last tracking period.

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). For each technology or sector, *TCEP* examines recent trends, tracks progress and recommends further action.

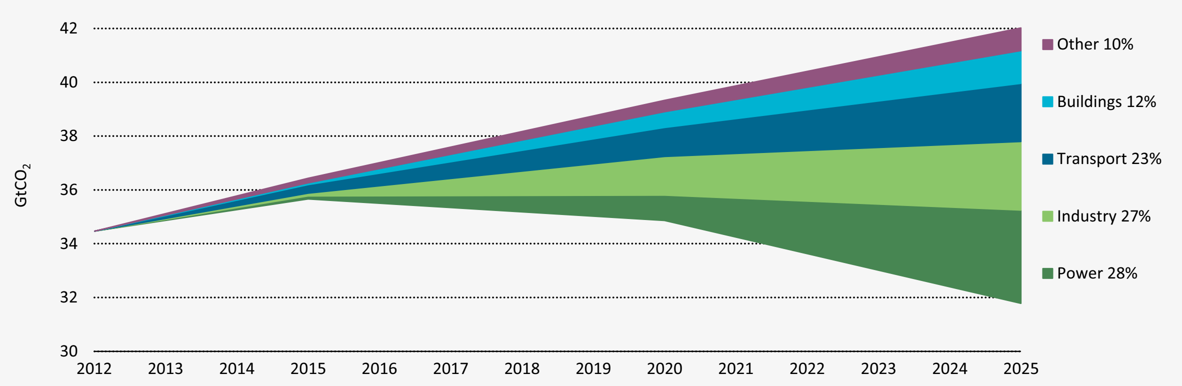
Recent trends are assessed with reference to the three *TCEP* measures that are essential to the success of individual technologies:

- **Technology penetration.** What is the current rate of technology deployment? What share of the overall energy mix does the technology represent?
- **Market creation.** 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.** Are technology reliability, efficiency and cost evolving, and if so, at what rate? What is the level of public investment for technology RD&D?

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

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

Figure 2.1 Sector contributions to emissions reductions



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

Table 2.1 Summary of progress

Status against 2DS targets in 2025		Policy recommendations
🟧 **Renewable power** ↗	Renewable power is increasingly at risk of falling short of ETP 2DS target, despite the growing competitiveness of a portfolio of renewable technologies.	■ Policies that enable a predictable and reliable long-term market are imperative to mitigate the risks associated with capital-intensive investment in renewables. ■ Regulatory frameworks that support cost-effective remuneration are needed, to avoid high economic incentives and the possibility of retroactive steps. ■ Developing markets should follow well-established best practices to avoid problems with integration.
🟥 **Nuclear power** ~	Conservative estimates put installed capacity at 24% below the 2DS target for 2025, with policy and financing uncertainties contributing to nuclear being off track.	■ Electricity market incentives that promote all types of low-carbon solutions are required to provide financing certainty for investments in nuclear power. ■ Policy recognition of the security of supply, reliability and predictability that nuclear power offers.
🟧 **Gas-fired power** ~	Despite improved flexibility of gas-fired power plants, renewable energy and low coal prices make the situation for gas power challenging.	■ Electricity market incentives such as carbon prices and other regulatory mandates are necessary for natural gas to compete with low-cost coal in the power sector. ■ Policy makers and manufacturers need to tailor solutions by application and location in order to maximise the advantage available from natural gas-fired power technologies.
🟥 **Coal-fired power** ~	The continuing trend of year-on-year growth in coal-fired power needs to be reversed to meet 2DS targets.	■ Policy incentives such as carbon pricing and regulation are imperative to control pollution and limit generation from inefficient units. ■ New coal power units should achieve best available efficiency and, if not initially installed, should be CCS-ready to have the potential to reduce the impact of coal use
🟥 **CCS** ↗	While progress is being made, CCS deployment is not on track to meet 2DS targets.	■ Financial and policy commitment to CCS demonstration and deployment are needed, to help mitigate the investment risk and long lead time required to discover and develop viable storage sites. ■ Policy incentives such as carbon pricing and regulation are required as currently CO_2 for use in enhanced oil recovery (EOR) remains the only commercial driver for carbon capture projects.
🟧 **Industry** ~	Despite progress in energy efficiency energy use must be cut 13% and direct CO_2 emissions 18% by 2025 compared with current trends. Demonstration activities of innovative low-carbon industrial technologies need to be accelerated to meet 2DS targets.	■ Focus on improving energy efficiency, switching to lower-carbon and alternative fuels, and deploying BATs to the greatest extent possible in all sub-sectors. Instruments such as stable, long-term CO_2 pricing mechanisms and the removal of fuel subsidies should be implemented to properly incentivise energy efficiency. ■ Support mechanisms to reduce investment risk and to accelerate demonstration and deployment of innovative technologies, as well as co-operative frameworks for international collaboration and technology transfer which manage intellectual property and competitive advantage concerns. Regional and sectorial disparities illustrate the need for co-ordinated efforts.

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
Iron and steel ~	Steady growth in crude steel production, particularly in emerging economies, puts more pressure on the need to limit annual growth in energy use to 1.1% through 2025 (half of the increase in 2012), along with direct CO_2 emissions.	■ Improve energy efficiency, phase out outdated technologies, switch to low-carbon fuel based processes (e.g. gas-based DRI) and recycle more steel to increase scrap availability, while addressing the challenges of slow capacity stock turnover, high abatement costs, fluctuation in raw material availability, carbon leakage and industrial competitiveness. ■ Support research, development, demonstration and deployment (RDD&D) programmes that will bring new technologies to commercial maturity and accelerate their diffusion to meet the 2DS.
Cement ~	Energy use must decline by 3% through 2025, despite cement production growth of 17%. Compared with current trajectory, direct CO_2 emissions need to be reduced by 12%.	■ Incentivise improvements in thermal energy intensity, clinker substitution and switching to low-carbon fuel mixes to capture potential improvements in energy use and emissions. ■ Demonstrate CCS in the short term to enable direct emissions reduction from cement manufacturing in the longer term, through globally co-ordinated efforts.
Transport ~	Meeting the transport 2DS targets requires a reversal of current trends, for both annual energy use and CO_2 emissions.	■ Policy instruments are required to rationalise travel choices, shifting part of the passenger transport activity to collective transport modes, particularly in areas of high urban density. Including economic instruments such as fuel taxation, road charging (e.g. associated with the usage of freight transport vehicles on the road network), congestion charging and parking fees. ■ Remove fuel subsidies to incentivise switching to fuel-efficient vehicles.
Fuel economy ↗	OECD PLDV efficiency improvement rates of 3% per year have not been matched by the larger and growing non-OECD market, leading to a global annual average improvement of 1.8%, almost half the rate required to meet 2DS targets.	■ Replicate the success in improving the average fuel economy of the PDLV fleet in the light commercial and medium- and heavy-duty vehicle fleets to drive efficiency improvements in the road freight sector. ■ Promote switching from larger, more powerful PLDVs towards smaller and/or less powerful vehicles. ■ Introduce a global realistic test cycle and better monitoring of the real on-road fuel economy.
Electric and hybrid-electric vehicles ↗	Annual average passenger electric vehicle sales growth rates of 50% are short of the 80% needed to meet 2DS targets.	■ Continuing RD&D, infrastructure roll-out and government incentives are required to support the development of passenger electric vehicles (EVs), particularly to increase vehicle range and reduce battery costs. ■ Promote EVs for transport modes other than passenger transport vehicles. ■ Explore the potential that electric mobility offers from changes in traditional vehicle ownership patterns to multi-modal travel and behavioural changes from enhanced use of information and communication technologies (ICTs).

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
Buildings 🔴 ~	Year-on-year growth of buildings energy demand is incompatible with 2DS targets, which require constrained growth between now and 2025, despite a predicted increase in population.	■ Governments need to promote deep energy renovation during normal refurbishment, only incentivising very high-performing buildings and components. ■ To achieve near-zero-energy buildings (NZEBs), building codes for insulation and windows with lower U values, along with mandatory air sealing, will be essential. ■ All governments – especially in emerging economies – need to make more effort to develop, promote and enforce more stringent building codes.
Building envelopes 🔴 ~	The potential to save energy in buildings by 75%-80% compared with existing buildings through advanced building envelope materials and construction techniques is not being realised.	■ Policies that promote awareness, education and financial incentives for very high-performing products and systems are necessary to increase adoption of the most efficient building envelope materials and construction. ■ Labelling and minimum performance standards for building components need to be enforced to accelerate the deployment of best available technologies. ■ International co-operation is needed to help establish commodity-based advanced building materials and products in emerging markets.
Appliances and equipment 🟠 ~	To meet 2DS targets the annual growth of electricity consumption in the buildings sector needs to halve, relative to growth in the last decade.	■ Appliance minimum energy performance standards (MEPS) need to be extended to more countries and appliances, particularly for digital and network-connected appliances. Monitoring and evaluation of the standards and their impact are also needed. ■ Stringent standards and enforcement are required to eliminate inefficient appliances from the market.
Co-generation and district heating and cooling 🟠 ~	The benefits of co-generation and district heating and cooling (DHC) systems, both through their direct energy efficiency, and through the increased flexibility that they provide to the electricity and thermal grids, have not been fully captured.	■ Strategic planning of local, regional and national heating and cooling should be developed to identify cost-effective opportunities to efficiently develop co-generation and expand DHC networks. ■ Policy measures are needed to facilitate investment in modernising and improving existing DHC networks and make them more energy efficient. ■ Policies should be implemented to mitigate high up-front costs and inflexible business structures, and address the lack of long-term visibility on regulatory frameworks that also limit co-generation and DHC.
Renewable heat 🟠 ~	Modern renewable heat deserves greater attention by policy makers, and should be included in low-carbon energy strategies that are based on a detailed local appraisal of both potentials and barriers.	■ Policy measures to raise awareness and tackle non-economic barriers can be a very cost-efficient way to tap into the potential of renewable heat given the maturity of many modern renewable heating technologies. ■ Success of targets and support policies in a number of regions need to be replicated.

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
Smart grids ● ~	The transition of smart grids from a perceived exclusive enabling function for renewable and distributed generation to the function of grid stabilisation and security of electricity supply signals the maturity of the concept and technology.	■ Regulation that enables cost-reflective investment in advanced distribution network technologies is required for sustained market development. ■ Market mechanisms are necessary to ensure that customers and suppliers share the smart-grid costs and benefits. ■ Support the development of international standards to accelerate RDD&D.
Energy storage ● ↗	Storage can contribute to meeting the 2DS by providing flexibility to the electricity system and reducing wasted thermal energy.	■ Policies are required to support market development of energy storage and the regulatory environment needs to adapt to recognise and compensate storage for the variety of energy solutions it provides to both the electricity and thermal energy systems.
Hydrogen ● ~	Hydrogen has the potential to contribute to meeting the 2DS as a flexible near-zero-emissions energy carrier with potential applications across all end-use sectors.	■ Targeted investment in RD&D for both stationary and transportation applications, as well as energy system integration, is needed to establish the role of hydrogen technologies in a broader energy system. ■ Support the development of international standards for hydrogen storage production and delivery.

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 generation continues to progress, but is not fully on track to meet the 2DS. Renewable electricity generation is expected to grow by 45% between 2013 and 2020, reaching 7 310 terawatt hours (TWh). With annual capacity additions expected to level off, however, renewable power is increasingly at risk of falling short of the 2DS generation target of 10 225 TWh by 2025, mainly because of slow economic growth, policy uncertainty in OECD member countries and persistent economic and non-economic barriers in OECD non-member economies.

Recent trends

In 2014, global renewable electricity generation rose by an estimated 7% (350 TWh) and accounted for more than 22% of the overall generation. OECD non-member economies continued to dominate global renewable generation, with their share increasing to around 55%. China remained the largest market, accounting for an estimated 23% of overall renewable electricity generation in 2014.

In 2014, cumulative installed renewable capacity increased further. Onshore wind additions recovered and are back on track; over 45 gigawatts (GW) of new capacity was installed globally, as the market in the United States picked up. China remained the largest annual onshore wind market globally with a record number of installations in 2014 of around 20 GW. Additions in China were significantly higher than the annual deployment in 2013 as developers rushed to finish projects before the feed-in tariff was cut by between 3% and 4%. The United States added close to 5 GW, followed by Germany (4.3 GW), Brazil (2.7 GW), and India (2.3 GW).

Solar photovoltaic (PV) capacity grew by an estimated 40 GW in 2014, slightly more than the previous year. Strong expansions in Asia continued, particularly in China (10 GW) and Japan (9 GW). Asia installed close to 50% of new solar PV capacity. Growth in the United States was higher than the previous year, with around 6.5 GW installed. Annual growth in OECD Europe was led by Germany and the United Kingdom (UK), each installing around 2 GW.

Hydropower additions decreased slightly, as China had commissioned large capacity earlier than expected, in 2013. Offshore wind additions in Europe decreased slightly to 1.5 GW due to grid connection delays. Asia's large offshore wind potential remained largely untapped. Two large solar thermal electricity (STE) plants were partially operational in the United States (Ivanpah, 333 MW; and Crescent Dunes, 100 MW), but several other STE projects faced financing challenges. In 2014, geothermal additions increased as large projects were commissioned in Indonesia, Kenya, Turkey and the United States.

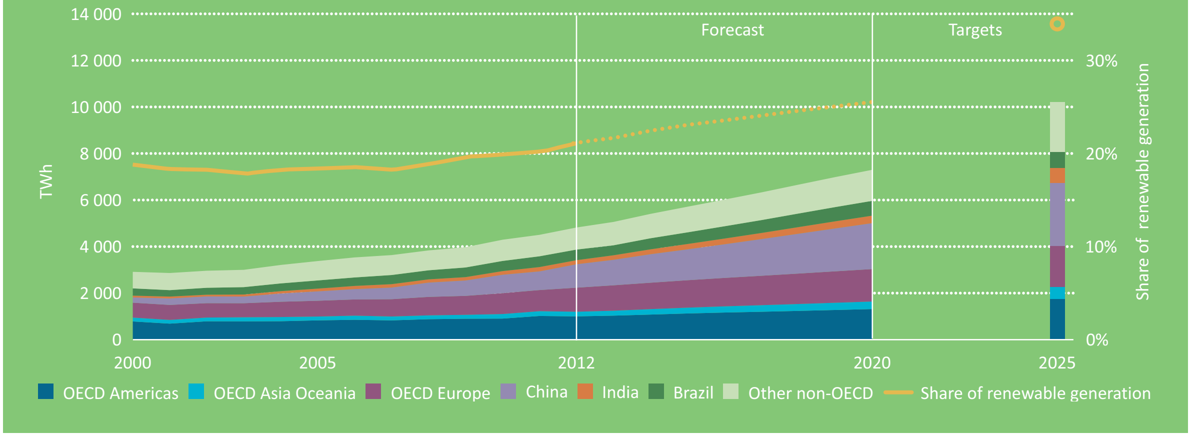
Early estimates indicate that total investment in new renewable capacity reached around USD 250 billion in 2014, with solar PV attracting the majority of investment, followed by onshore wind. According to Bloomberg New Energy Finance (BNEF, 2015), the financing of new projects showed an upward trend over the last year for utility-scale solar PV and offshore wind projects, signalling a positive outlook.

Although renewables are still more expensive in general than conventional power generating technologies, the gap has narrowed significantly over the last decade. In some countries, some renewables are competitive with new-built fossil fuel generation.

Similarly, utility-scale solar PV installations are already competitive in some places. In Chile and Mexico, two utility-scale solar PV plants are operational on the spot market. In Texas, a solar plant became partially operational without a power purchase agreement (PPA) for the first time. More projects are under construction and expected to be online in 2015.

In locations with good irradiation levels and high electricity spot prices, PPAs with record low prices were signed over the last year. In Brazil, developers signed PPA contracts for 1 GW of capacity averaging USD 87 per megawatt hour (MWh) to deliver power by 2017. In the United Arab Emirates, projects submitted bids as

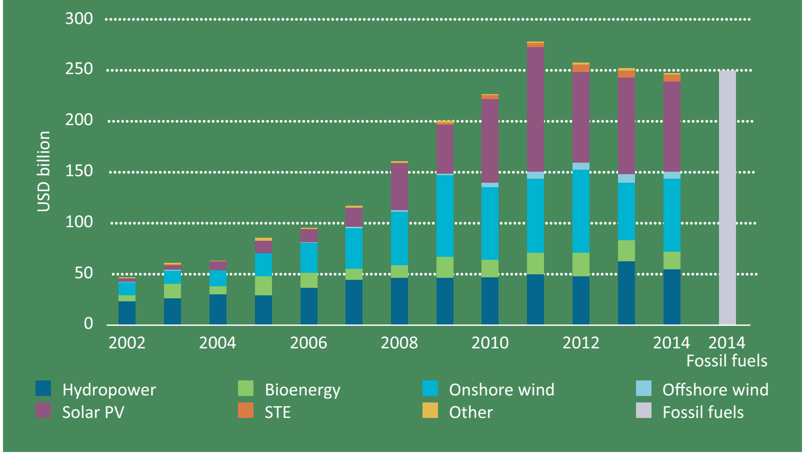
2.2 Renewable power generation by region



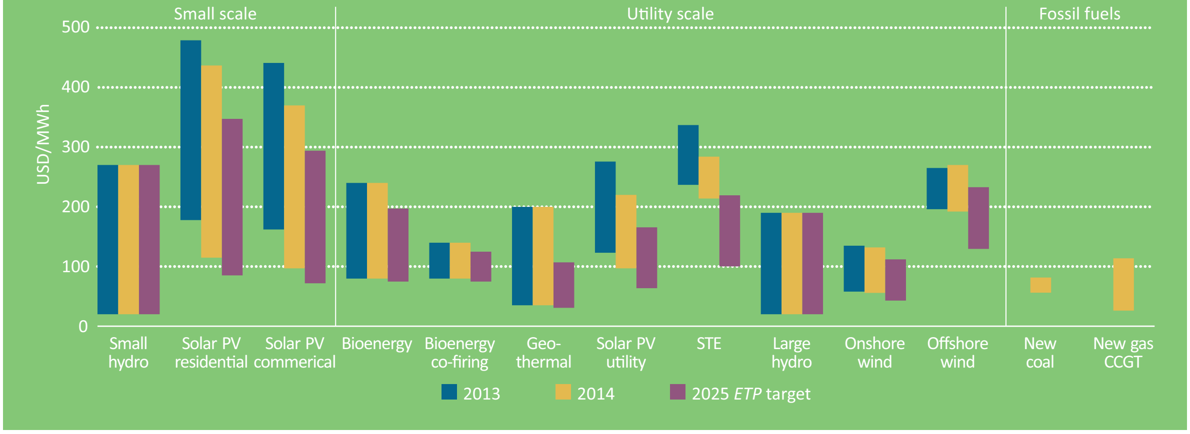
23%

OF GLOBAL RENEWABLE GENERATION CAME FROM CHINA, THE LARGEST MARKET IN 2014

2.3 Renewable capacity investment



2.4 Levelised cost of electricity



For sources and notes see page 133

low as USD 59/MWh. Developers in El Salvador, Panama and Uruguay signed PPAs or offered bids ranging from USD 90/MWh to USD 140/MWh.

Over the past year, growth in both residential and commercial distributed solar PV sectors was robust in countries where the levelised cost of energy (LCOE) of systems fell below the variable portion of retail electricity prices. In the absence of remuneration of excess electricity, the share of self-use, the overall cost of the project and financing are important factors for a profitable investment. In addition, if there is a good match between demand and generation, higher shares of self-consumption mean less stress on the grid. In Australia, Germany, Italy and the Netherlands, where retail electricity prices are high, some projects with good financing are already profitable depending on the share of self-consumption. The increase of distributed solar PV generation has posed challenges to the fair allocation of fixed-grid costs, which need to be addressed.

In Japan, booming solar PV market deployment has been driven by generous feed-in tariffs, which have raised concerns over the overall cost associated with this deployment. It has also posed integration challenges because developers have proposed PV projects in locations where land is cheap but demand is low and grid capacity is limited. In some provinces, utilities have refused to connect projects where the grid is already highly congested. Grid integration was also a challenge in South Africa, where some solar PV and wind projects could not get a timely grid connection. This contributed to delays in the third and fourth rounds of renewable tenders.

Over the past year, onshore wind continued to improve its competitive position. New turbine technology with larger rotor diameters has unlocked more low and medium wind resource sites, increasing the number of bankable projects, especially in Europe and the United States. In the interior region of the United States, PPAs were signed as low as USD 20/MWh (around USD 43/MWh including production tax credit, or PTC). In Brazil, PPA prices further increased from USD 47/MWh to USD 54/MWh, mainly due to the new grid connection rule where developers are responsible for all associated costs. In Uruguay, the first projects with PPAs – signed in 2011 – ranging from USD 50/MWh to USD 65/MWh came online over the past year.

Offshore wind costs remained high over the past year. This pushed some countries to lower their targets or delay projects. Germany lowered its 2020 offshore wind capacity target from 10 GW to 6.5 GW, while Denmark delayed auctioning a 600 megawatt (MW) project. By contrast, some countries in Asia – China, Japan and Korea – increased their support to boost the offshore industry. However, more time is needed to see how this affects actual deployment. Costs also remained high for ocean energy, with only a few demonstration projects in operation globally. Two of the largest ocean energy companies announced that they would not invest further in developing ocean technology.

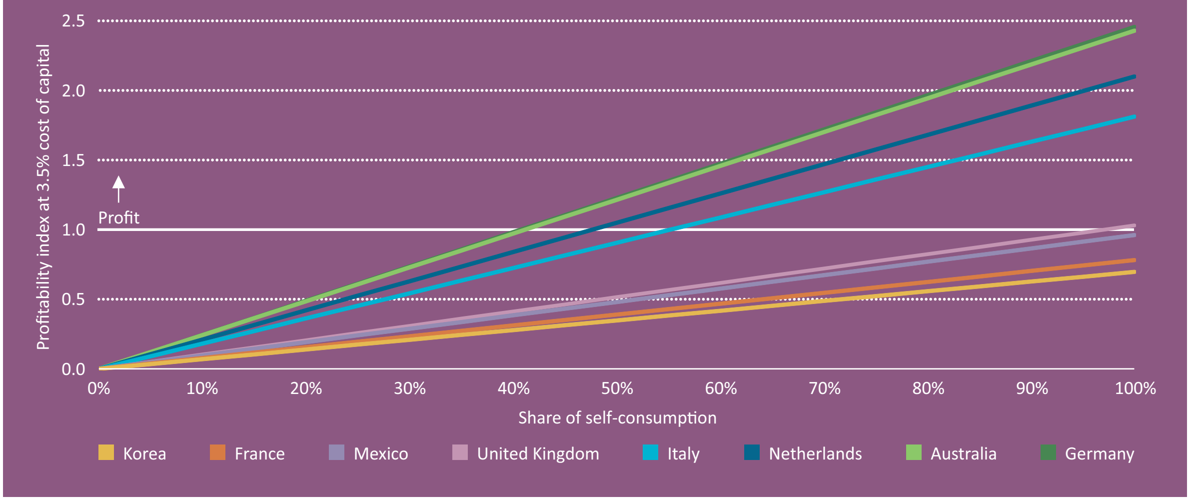
Policy remains vital to the competitiveness and deployment of renewable energy technologies. In 2014, policy signals were mixed. Although ambitious new renewable energy targets were announced in China and India, policy uncertainty and retroactive changes elsewhere posed challenges for renewables. In October 2014, European Union (EU) leaders committed to reduce GHGs by at least 40% and increase energy efficiency and renewables by at least 27% by 2030. Both of these targets are binding, but only at the EU level. Furthermore, the governance around the new policy to achieve the targets remains unclear, creating uncertainty for renewable energy investments.

In addition to policy uncertainty at the EU level, some countries in Europe introduced retroactive measures harming renewable deployment. Spain finalised the new retroactive remuneration scheme that ended feed-in tariff payments and replaced them with annual payments based on a calculation of a fixed "reasonable annual return" of 7.4%. Bulgaria cut solar PV feed-in tariffs retroactively, assuming that the country had already met its 2020 renewable energy target. In Romania, the government decided to halve the number of certificates provided to both wind and solar PV. Retroactive policy changes were also introduced in Italy for solar PV installations larger than 200 kilowatts (kW).

In the United States (US), policy volatility persisted. In December 2014, the PTC for onshore wind projects was extended for just a few days through the end of 2014. Meanwhile, the US Environmental Protection Agency (US EPA) announced its new Clean Energy Plan. The details and implementation of the plan are expected by June 2015, and its impact on renewable deployment remains to be seen.

Mexico launched a major energy market reform, which included liberalising the electricity market. Neutral green certificates were introduced to promote clean electricity. Rules and implementation of this policy remain uncertain while investors are currently in wait-and-see mode.

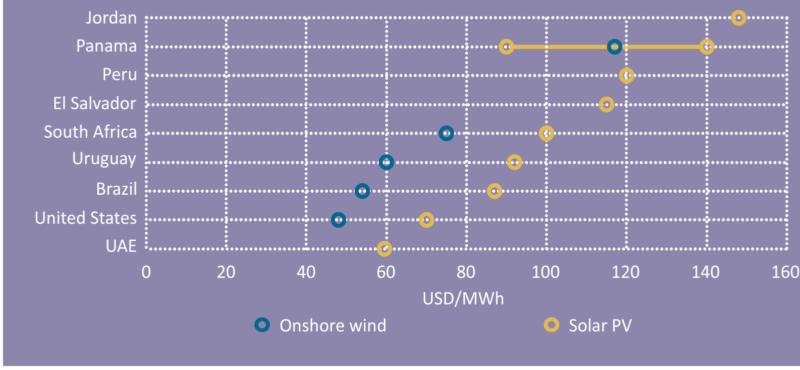
2.5 Profitability index of a residential PV system



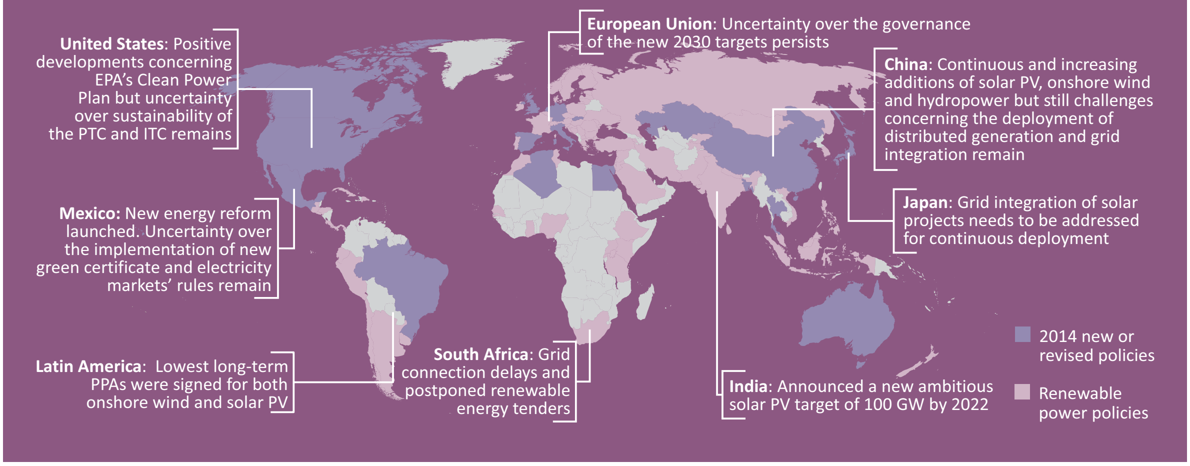
Key developments

Record-low long-term remuneration contract prices for onshore wind and solar PV were achieved in 2014. In some countries, renewables were the preferred option to new-built fossil fuel generation.

2.6 Wind and solar PV tender results or offered bids



2.7 Renewable power policies



United States: Positive developments concerning EPA's Clean Power Plan but uncertainty over sustainability of the PTC and ITC remains

Mexico: New energy reform launched. Uncertainty over the implementation of new green certificate and electricity markets' rules remain

Latin America: Lowest long-term PPAs were signed for both onshore wind and solar PV

South Africa: Grid connection delays and postponed renewable energy tenders

European Union: Uncertainty over the governance of the new 2030 targets persists

China: Continuous and increasing additions of solar PV, onshore wind and hydropower but still challenges concerning the deployment of distributed generation and grid integration remain

Japan: Grid integration of solar projects needs to be addressed for continuous deployment

India: Announced a new ambitious solar PV target of 100 GW by 2022

For sources and notes see page 133

Tracking progress

Despite the growing competitiveness of a portfolio of renewable technologies, the growth of additional annual capacity is slowing down due to sluggish economic growth, policy uncertainty in OECD member countries, and persistent economic and non-economic barriers in OECD non-member economies. Thus, for the first time the *TCEP* evaluation is that renewable power improvement is needed to meet the targets of the *ETP 2015* 2DS scenario.

Renewable electricity generation is expected to grow by 45% between 2013 and 2020, reaching 7 310 TWh, and is currently at risk of falling short of the 2DS target of 7 537 TWh. If current trends continue, the shortfall will increase even further by 2025, when the 2DS target is 10 225 TWh. This result is subject to strong regional differences across technologies and regions.

Hydropower deployment needs improvement to reach its 2DS generation target. Over the medium term, new additions of hydropower capacity are expected to fall in OECD member countries, mainly due to decreasing resource availability. In OECD non-member economies, new additions are expected to be strong, but environmental concerns and lack of financing pose challenges to large-scale projects. Deployment trends in China and global precipitation levels may change this picture by 2025.

For onshore wind, the second-largest renewable technology, improvement is needed in capacity growth rates to meet 2DS targets. Policy uncertainty in OECD member countries is expected to affect deployment over the medium term, including doubts over governance of the European Union's 2030 climate change goals and the extension of the production tax credit in the United States. In OECD non-member economies, onshore wind is expected to grow, especially in China, Brazil and India. However, integrating large amounts of new onshore wind power remains a challenge, especially in China.

Solar PV is the only technology on track to meet its 2DS power generation target by 2025. Its capacity is forecast to grow by 18% annually between 2014 and 2020. This growth should be stable in OECD member countries, with decreasing annual additions in Europe and strong expansion in Chile, Japan and Mexico. In OECD non-member economies, growth of solar PV should spread geographically. Deployment trends in China are strong with improving economics and growing distributed generation opportunities. If these medium-term trends continue, solar PV could even surpass its 2025 target.

Offshore wind, geothermal, STE, bioenergy and ocean power are not on track due to technology-specific challenges. For offshore wind, OECD member countries, particularly in Europe, are expected to lead deployment over the medium term. Some countries and companies have announced ambitious targets to decrease costs by 2020, but grid delays and financing challenges have often made it difficult to realise similar ambitions. OECD countries could reach their 2DS targets if those challenges are addressed. Deployment is falling behind in OECD non-member economies, however, especially in China, as investment costs remain high and technological challenges persist.

Total investment costs remain high for STE, slowing the pace of deployment. The potential for electricity generation from geothermal energy is largely untapped. Pre-development risks remain high and only a handful of countries have introduced policies to address those risks. For bioenergy, sustainability challenges and long-term policy uncertainty have been decreasing the bankability of large projects, particularly in OECD member countries. Ocean power is still at the demonstration stage, with only small projects deployed.

Recommended actions

Despite a portfolio of renewables becoming more competitive in a wider set of circumstances, policies remain vital to stimulating investment in renewables. Many renewables no longer need high economic incentives, but they do need long-term policies that provide a predictable and reliable market and regulatory framework compatible with societal goals.

Given their capital-intensive nature, renewables require a market context that ensures a reasonable and predictable return. Financing costs play a large role in determining generation costs for capital-intensive renewables. Policy and regulatory uncertainties create higher risk premiums, which directly undermine the competitiveness of renewables, so policy risk is an important barrier to deployment.

Policy makers should focus on cost efficiency to prevent over-remuneration of some technologies, but changes must be predictable and retroactive changes must be avoided at all times. Countries beginning to deploy variable power plants should implement well-established best practices to avoid integration challenges. Markets with high variable renewable penetration 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 133

Nuclear power

● Not on track
~ Limited developments

Global nuclear generation increased slightly between 2012 and 2013, but remains about 10% lower than in 2010. At the beginning of 2014, 72 reactors were under construction, the highest number for more than 25 years. But in 2014 there were only three construction starts (down from ten in 2013), and five grid connections (representing 5 GW, up from 4 GW in 2013).

Recent trends

The European Commission approved the United Kingdom's Contracts for Difference scheme for the construction of the Hinkley Point C nuclear power plant, paving the way for further new-build projects in the United Kingdom and other European countries in the coming decade. In Japan, all operable reactors have remained idle pending safety reviews. The Nuclear Regulation Authority has approved restarting the two units of the Sendai plant, as well as Takahama units 3 and 4. These restarts could be effective in the first half of 2015. Construction of the Akkuyu nuclear power plant in Turkey, the country's first, is expected to start in 2015 (under the build-own-operate model offered by Russia). In Poland, the first nuclear power plant could be under construction before 2020 if a suitable financing model is found. Hungary secured a loan from Russia for two new units, which also could be under construction before 2020. A new energy plan developed by the government of the Republic of Korea calls for the construction of nine new reactors by 2023. In the United States, besides the five units under construction, there remains interest in long-term operation of the existing fleet. The Nuclear Regulatory Commission has resumed licence renewals for nuclear power plants after a two-year hiatus; currently 74 reactors are licensed to operate up to 60 years, and applications are being reviewed for an additional 19 units. However, as many as six to ten merchant units could be shut down due to unfavourable economics despite receiving licences. Vermont Yankee, for example, shut down in December 2014 after 42 years of operation.

Developments in other OECD countries in 2014 could reduce nuclear generating capacity. France's lower house of parliament voted to reduce the share of nuclear power generation from 75% to 50% by 2025. In Sweden, where nuclear power accounts for more than 40% of generation, the short-lived coalition government proposed replacing the country's nuclear power plants with renewable technologies. Among OECD non-member economies, South Africa signed several agreements with countries that possess nuclear technology, in preparation for tenders that aim at securing up to 9.6 GW by 2030. China moved ahead with planning and construction of nuclear power plants, and development of its own Generation III technologies, such as the Hualong-1 design. It is also considering investments in projects in Argentina, Romania and the United Kingdom. In the United Arab Emirates, construction started on the third unit of the four-unit Barakah plant, which will provide 5.6 GW by 2020. Belarus is constructing its first two units with technical and financial support from Russia.

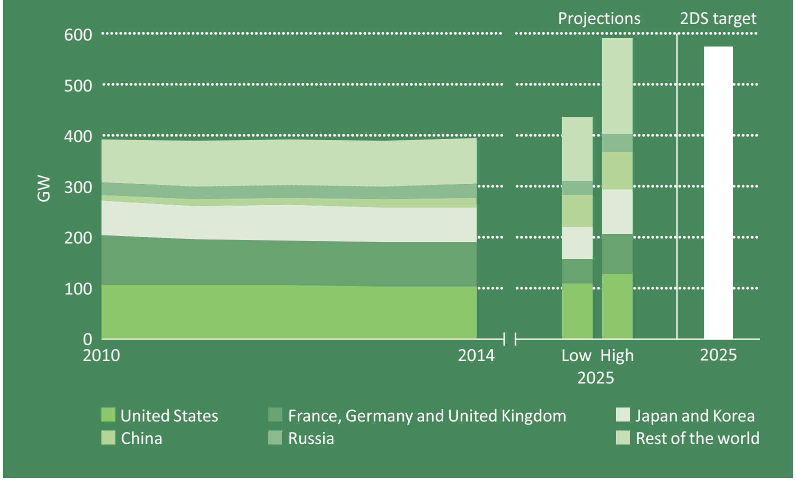
Tracking progress

According to the recently published "Red Book" from the Nuclear Energy Agency (NEA) and the International Atomic Energy Agency (IAEA), gross installed capacity currently at 396 GW is projected to reach 438 GW to 593 GW by 2025; in the 2DS, global nuclear capacity would need to reach 585 GW by that time. The range of projections is wide because policies concerning climate change mitigation are still unclear, the existing fleet will be in operation for a long time, financing is uncertain and China's new-build programme beyond 2020 has yet to be clarified, in particular with respect to inland power plants.

Recommended actions

Recent geopolitical events, and the realisation that swift action is needed to reduce GHG emissions and air pollution from fossil-based generation, have highlighted the potential of nuclear power to increase energy security, diversify fuel supply and lower emissions. This awareness has yet to be translated into policy support for long-term operation of the existing fleet and construction of new plants, particularly in Europe. There is a need to introduce market incentives to favour all low-carbon technologies, through carbon taxes or electricity market arrangements, or both, and to recognise the vital contribution that nuclear energy can make.

2.9 Installed gross nuclear capacity



5

GW CAPACITY INCREASE IN 2014 TO A TOTAL OF

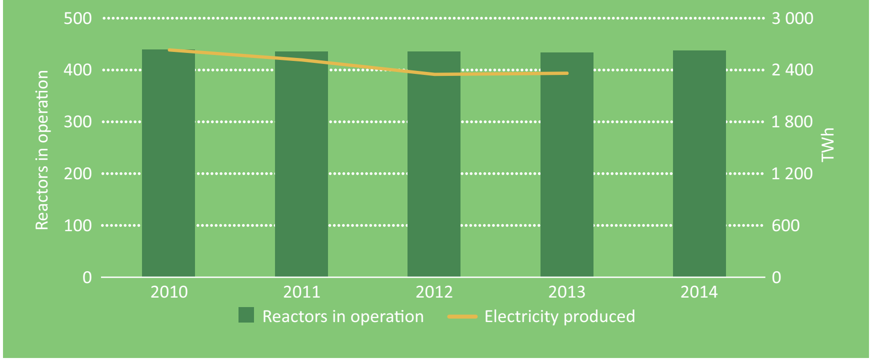
438

OPERATIONAL REACTORS

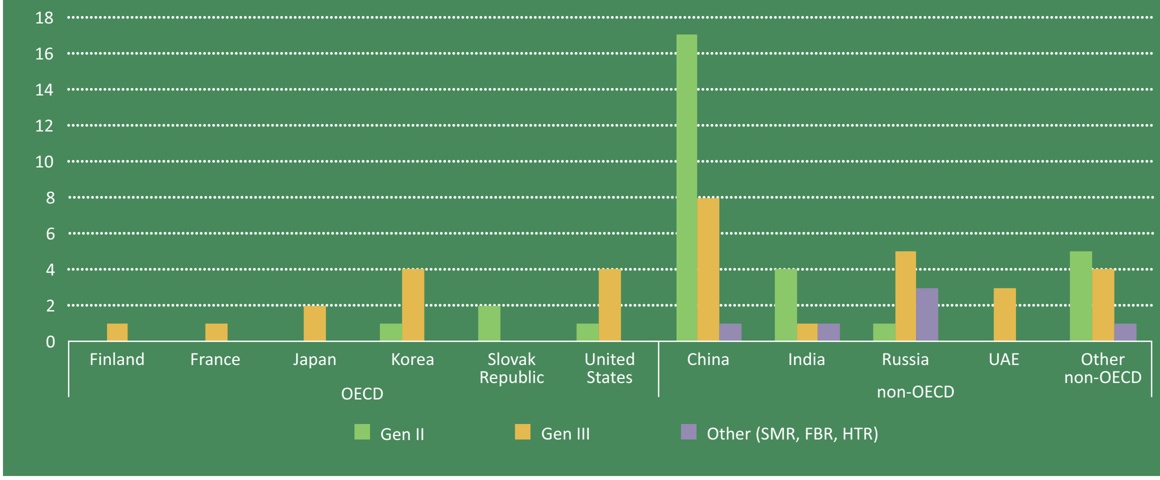
Construction trends

47% of all reactors under construction are third-generation nuclear, 44% are second-generation and 9% other

2.10 Operable reactors and electricity production



2.11 Reactors under construction



For sources and notes see page 133

Natural gas-fired power

● Improvement needed

~ Limited developments

Natural gas-fired power generation accounted for 22% of total global power generation in 2012 (5 104 TWh). While this share is projected to decrease, generation is likely to continue to grow over the next two decades, playing a major role in reducing the carbon intensity of power generation globally.

Recent trends

Global natural gas demand slowed markedly in 2013, increasing at an average of just 0.8%, compared with 1.8% in both 2011 and 2012. The power sector accounted for the bulk of the weakness in OECD member country demand. Gas-fired generation dropped sharply in 2013, as electricity consumption fell in the United States and Europe. In the United States, a rebound in gas prices allowed coal generation to regain market share. In Europe, under pressure from renewable technologies and coal, gas-fired generation fell for a third consecutive year in 2013, to stand some 30% below its 2010 level.

For 2014, gas demand in the OECD power sector is poised to move less dramatically than during the previous two years. Gas use for electricity generation in the United States remained broadly flat in 2014 until October, with the impact of further moderate gas price gains offset by growing electricity demand. In some European countries, including Spain and the United Kingdom, gas consumption in the power sector was showing smaller year-on-year reductions in 2014. In the United Kingdom in particular, the sharp fall in gas prices made gas more attractive than coal. In OECD non-member economies, growth in gas consumption was also considerably slower than usual in 2013 and, outside China, it barely increased. And many countries face gas shortages, particularly in Africa and the Middle East, as the costs of development of new fields are higher than subsidised domestic prices.

Liquefaction capacity stood at roughly 400 billion cubic metres (bcm) globally at the end of 2013, with an additional 150 bcm under construction. The next wave of liquefied natural gas (LNG) supplies will be dominated by Australia and the United States. Governments remain divided on shale gas exploration policy, and geological uncertainty is high. In China, the original 2020 shale gas production target of 60 bcm to 100 bcm has recently been downgraded to 30 bcm. In India, the government inaugurated a shale gas policy in late 2013 and the first wells have been drilled, but commercial production is some time away. In Europe, a handful of countries have banned hydraulic fracturing (fracking) while others are issuing exploration licences. So far, test drilling has shown less favourable conditions than in the United States, and local opposition remains strong in many places. The plunge in oil prices during 2014 – and associated oil-linked gas prices – adds a further obstacle.

High cycle efficiency that includes quick start-up time, low turndown ratio, good ramping capabilities and part-load behaviour are now major gas turbine design parameters. Although reciprocating gas engines are unable to match the efficiencies of state-of-the-art combined-cycle gas turbines (CCGTs), they are becoming increasingly attractive. They are robust, offer flexible operation, accept a wide range of fuels, are effective for co-generation[2] and can be stacked to match the capacity required.

Tracking progress

Natural gas-fired power is needed in the 2DS to provide grid flexibility to support the integration of variable renewables and as a lower-carbon alternative to coal-fired generation. While natural gas-fired electricity generation increases in meeting 2DS projections over the next decade, its share would fall by 1 to 2 percentage points by 2025. In fact, growth in gas-fired generation over the period falls to less than 2% annually from the 5.2% annual average growth observed over the last decade.

Recommended actions

As regional differences in the energy mix and in gas prices widen, policy makers and manufacturers need to remain responsive to market demands, including operational flexibility, high efficiency through the load range and fuel flexibility. In co-generation mode, improvements in thermal storage technology would allow a CCGT to operate more flexibly. As designs are improved, the choice between CCGTs, open-cycle gas turbines (OCGTs) and stacked reciprocating engines will depend on each project's application and location.

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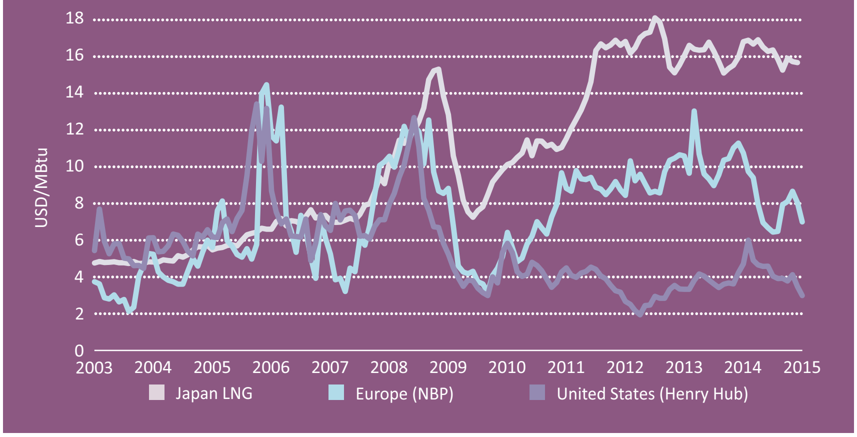
[2] Co-generation refers to the combined production of heat and power.

2.12 Natural gas spot prices

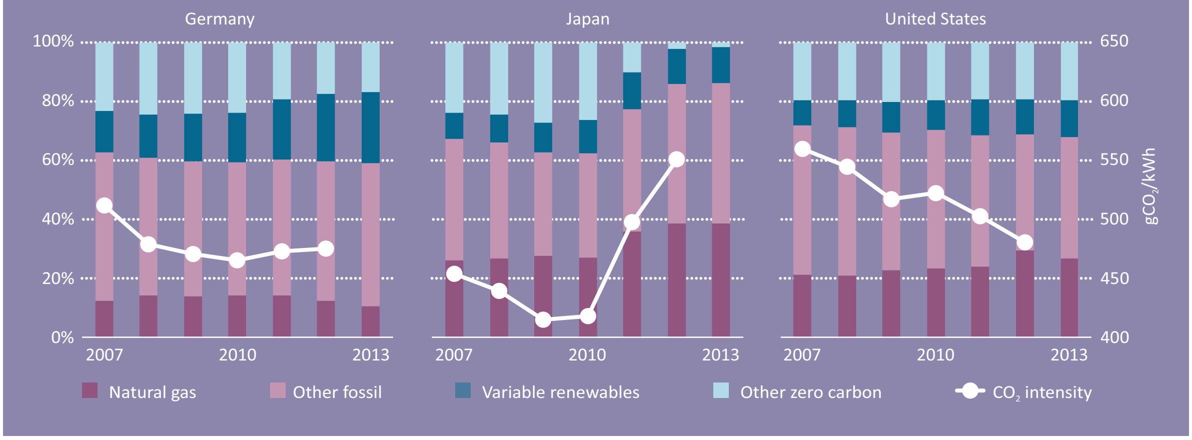


Coal-to-gas or gas-to-coal?

Natural gas continues to struggle against cheap coal in the power sector

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

2.13 Power generation mix and related CO_2 intensity



EU CO_2 PRICE

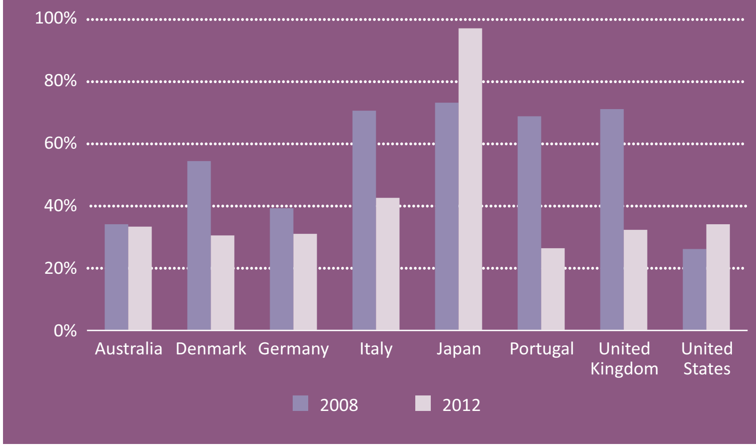
42 €/tCO_2

FOR SHORT-TERM COAL-TO-GAS GENERATION SWITCH

20 €/tCO_2

LONG-TERM CAPACITY INVESTMENT SWITCH

2.14 Natural gas-fired power capacity factors



For sources and notes see page 133

Coal-fired power

● Not on track

~ Limited developments

Global coal-fired power generation continued its year-on-year growth in 2012. A decline in OECD member countries was more than compensated for by growth in OECD non-member economies. Indications for 2013 show growth in both OECD member and non-member economies.

Recent trends

Coal remains the fastest-growing fossil fuel, outpacing the growth of oil and gas in 2012. Although growth in demand for coal slowed, it still accounted for almost 30% of global primary energy consumption and more than 40% of electricity generated. In 2012, despite its weaker economic growth, China's share of global coal energy demand rose above 50%. In 2013, China was the largest coal consumer, followed by the United States and India, as in 2012; combined, these countries accounted for more than 70% of global coal demand. At the same time, the growth in generation from coal in OECD non-member economies in 2012 was 2.9% – the lowest in a decade.

In 2013, a combination of factors led to an increase in coal-fired generation. The weather was more severe than in 2012, gas prices were generally higher, and coal prices were lower, as a result of coal oversupply in world markets. In Japan, where coal-fired generation has increased to compensate for nuclear capacity taken off line after the Fukushima Daiichi accident in 2011, two new coal plants have led to higher coal consumption.

While there was a net increase in new coal plant capacity in OECD non-member economies of almost 80 GW in 2012, there was a net decrease in OECD countries of 14 GW. In the United Kingdom, 2 GW net coal generating capacity was retired in 2012 and 4.6 GW in 2013. In the United States, 10 GW net was retired in 2012 and 6 GW in 2013. Retirements in OECD countries were offset by a wave of new-build coal-fired units in Europe, for which financial investment decisions had been made when a set of particularly favourable circumstances came together around 2007-08. In Germany, for example, 2.7 GW of coal capacity came on line in 2012, followed by 5.6 GW in 2013. This wave of plants is unlikely to influence the more general trend of declining coal-fired generation in Europe.

In 2012, a net 53 GW of new coal plants was constructed in China, and more than ten times that capacity added over the last ten years. Unless plants are constructed for co-generation, China's policy is to build only supercritical or ultra-supercritical units, and permission to build new units is often granted at the expense of retiring some ageing capacity. In India, where 21 GW of new capacity came on line in 2012, building less-efficient subcritical units predominates. While India has a programme to build several supercritical ultra-mega power plants, policy measures to ensure that all new units have efficiencies consistent with supercritical or ultra-supercritical technology do not become effective until 2017. In Southeast Asia, where coal-fired capacity is also expanding, less-efficient subcritical units still dominate.

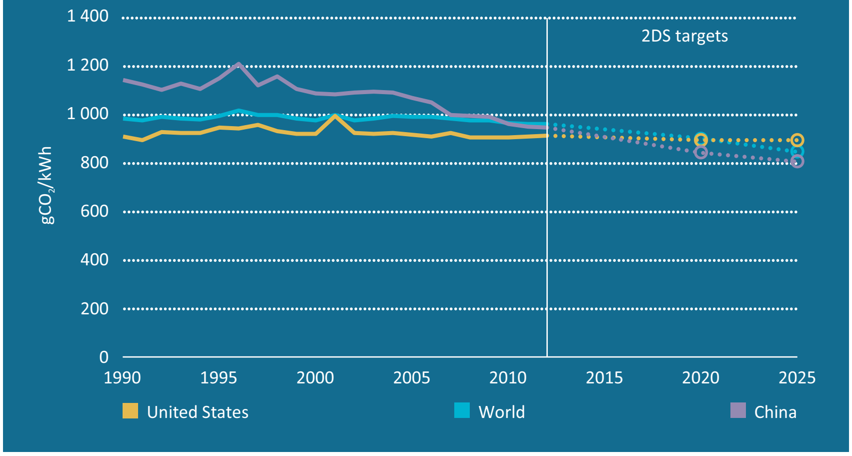
Tracking progress

While the annual average growth of CO_2 emissions from coal-fired electricity production from 2002 to 2012 was 3.7%, over the past five years this rate has halved. To meet the 2020 2DS targets, the growth in CO_2 must plateau and then fall. Given that China does not expect its emissions to plateau until closer to 2030 and given India's intentions to markedly expand coal consumption, the projected trajectory of emissions reduction from coal is not on track to meet 2DS projections.

Recommended actions

For CFPPs to be "future proofed" for operation in a low-carbon energy system, three principles need to be incorporated into their design. Wherever possible, CFPPs should offer the highest possible efficiency. CFPPs must be able to operate with sufficient flexibility to balance electricity supply and demand by compensating for variable supply from increasing renewable power. If not initially installed with CCS, CFPPs should be designed with future retrofit of CO_2 capture. Consideration given at an early stage may not only facilitate future retrofit of CCS but also reduce retrofit costs. It is vital that decisions on plant siting, which currently take into account needs such as fuel supply, cooling and grid connections, should also consider the future use of CCS by examining CO_2 transport connections and exploring access to large CO_2 storage capacity.

2.15 Coal-fired power generation CO$_2$ intensity

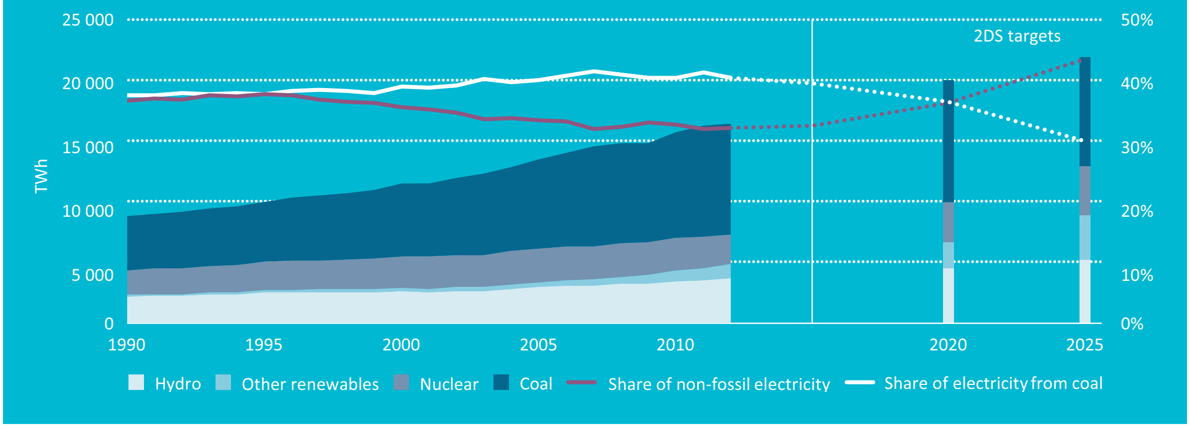


Key trends

Over the past 5 years the average annual increase in CO$_2$ emissions from coal-fired power generation has halved compared to the previous decade

Through a range of measures and practices, average annual fleet efficiencies continue to rise incrementally in both OECD countries and OECD non-member economies

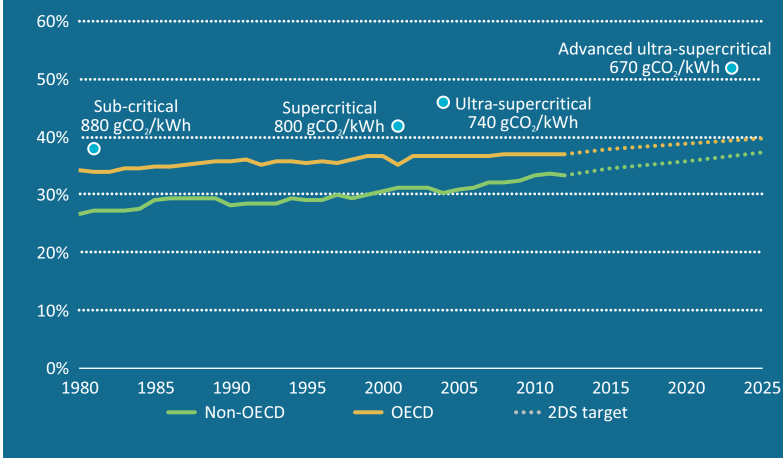
2.16 Coal and non-fossil power generation



40%

OF GLOBAL ELECTRICITY WAS GENERATED BY COAL IN 2012. THIS FALLS TO 30% BY 2025 IN THE 2DS

2.17 Average coal fleet efficiencies



For sources and notes see page 133

Carbon capture and storage

● Not on track
↗ Positive developments

Deployment of CCS passed a milestone in 2014 when CO_2 capture was demonstrated in a large-scale power plant for the first time. CCS investment needs to increase significantly, however, to ensure that enough projects are being developed to meet the 2DS.

Recent trends

In October 2014, SaskPower's Boundary Dam unit 3 in Canada became the world's first commercial electricity generating unit with full CO_2 capture. Around 1 million tonnes of CO_2 ($MtCO_2$) per year – 90% of CO_2 emissions from the unit – will be captured and stored underground through enhanced oil recovery (EOR). In Mississippi, construction of the Kemper Country energy facility continued, with the goal of commencing operations in 2016. And in Texas, the final investment decision was taken on the Petra Nova Carbon Capture project.

The three components of CCS – CO_2 capture, transport and storage – are now all being undertaken at commercial scale. By the end of 2014, 13 large-scale CO_2 capture projects were operating globally across five sectors, with the potential to capture up to 26 $MtCO_2$ per year. Over the past five years there has been a slow but steady increase in the number of CCS projects under construction. Final investment decisions were taken on two projects[3] in 2014, bringing the number of projects under construction to nine. A further 13 projects are in advanced stages of planning.

Of the 13 CO_2 projects operating, five store CO_2 with monitoring and verification focused on demonstrating storage permanence, while eight are using the captured CO_2 for EOR without storage-focused monitoring.

The demand for CO_2 for EOR in some places has created or strengthened the business case for carbon capture, enabling its demonstration. In the long term, however, all CO_2 storage, including for EOR, will need to be subject to monitoring and verification to account for the CO_2 stored.

The United States is leading the deployment of CO_2 capture, largely because of demand for CO_2 for EOR. Seven of the 13 projects in operation, and seven of the 22 in construction and development, are in the United States. To realise the 2DS CCS will have to increase markedly, particularly in OECD non-member economies which capture over half of the global total by 2025.

The USD 1 billion investment in the Petra Nova Carbon Capture project brings total global cumulative investment in large-scale CCS to USD 12 billion since 2005. OECD governments have made available USD 22 billion in support for large-scale projects, but much of this has not yet been spent.

Tracking progress

While CCS is making progress, it is well below the trajectory required to match the 2DS. At the end of 2014, 13 large-scale projects were capturing a total of 26 $MtCO_2$ per year, but only 5.6 Mt of the captured CO_2 is being stored with full monitoring and verification. The 35 projects currently in operation, under construction or in advanced planning have the potential to capture 63 $MtCO_2$ per year by 2025; however there remains a short window for additional projects to begin development in the coming years and be operating by 2025.

Recommended actions

Governments and industry need to work together to ensure that final investment decisions are taken on as many as possible of the projects in development. It is vital to keep a consistent stream of projects moving through construction to build experience and foster growth in the industry.

To meet the 2DS, the rate of CO_2 being stored per year will need to increase by an order of magnitude. Governments should invest now in characterising storage resources and ensure that all CO_2 storage is appropriately monitored and verified.

Governments should identify opportunities where policies and local and commercial interests align to encourage CCS deployment, and introduce measures targeted at creating new and strengthening existing markets.

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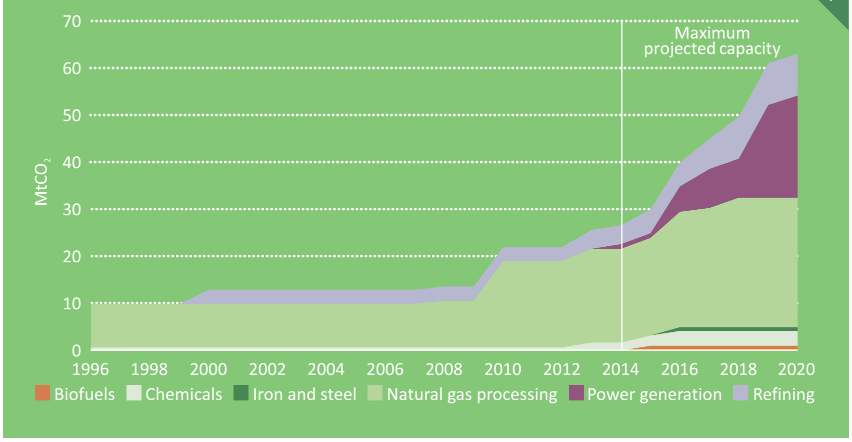
[3] Petra Nova Carbon Capture project and the Abu Dhabi CCS Project.

2.18 Large-scale CO_2 capture projects

More online



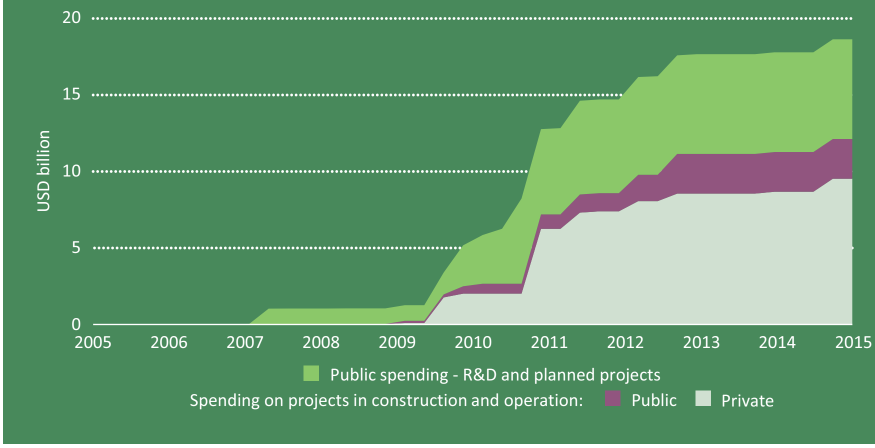
59%

OF GLOBAL CCS REQUIRED IN OCDE NON-MEMBER ECONOMIES BY 2025 IN THE 2DS

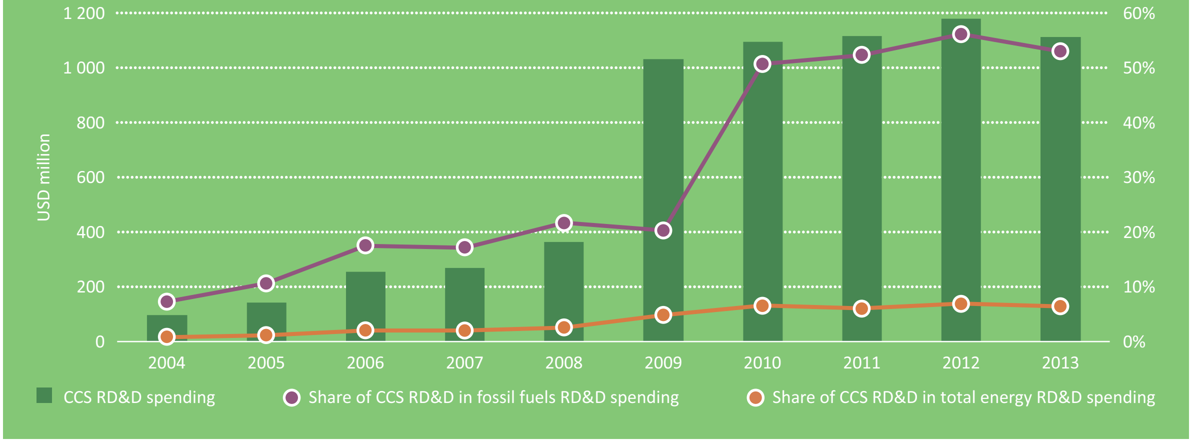
60

MILLION TONNES OF CO_2 STORED WITH MONITORING TO DATE

2.19 Cumulative spending on CCS projects



2.20 IEA public RD&D spending



For sources and notes see page 133

Industry

● Improvement needed
~ Limited developments

Global industrial energy intensity in 2012 was 12% lower than in 2000, primarily due to the addition of efficient capacity. Industrial energy use continues to grow, however. To meet 2DS targets, by 2025 energy use must be reduced by 13% and direct CO_2 emissions by 18% compared with the current trajectory.

Recent trends

Energy use[4] fell between 2011 and 2012 in most OECD countries, mainly due to a slowdown in material production growth, but increased significantly in other parts of the world. Aggregated industrial energy intensity decreased by 13% in the United States and by 4% in China, but rose in other regions, including Russia and India. These changes can be attributed partially to efficiency shifts, though structural changes and price effects also play roles.

Direct industrial CO_2 emissions decreased by 6% globally in 2012, to 8 389 $MtCO_2$, despite a 1% increase in energy use. The global fuel mix in industry shifted towards electricity, biofuels and waste. In Africa, however, fossil fuels' share of total energy use grew from 52% to 59%. CO_2 emissions per unit of industrial energy use decreased in all major regions except Africa and the Middle East, including 8% decreases in developing Asia and in the European Union.

In addition to the up-front financial barriers to implementing best available technologies (BATs) in new capacity, the long technical and economic lifetimes of industrial facilities can contribute to "technology lock-in" and hinder the improvement of overall efficiency. In some regions, overcapacity in the energy-intensive industrial sectors is increasingly becoming a concern. For example, in China, capacity utilisation in five major sectors was at or below 75% in 2012.[5] In response, the State Council has reduced capacity additions in these sectors, and encouraged industry to eliminate outdated and inefficient capacity (Central Government of the People's Republic of China, 2013). To limit total industry emissions in the long term, CCS will be required.

Energy management systems continue to gain prominence across the industrial sector. The number of International Organization for Standardization (ISO) 50001-certified sites[6] is increasing, but the majority of these sites are in OECD countries (Peglau, R., 2014). It is difficult to track actual energy savings as a result of this certification, or sectoral distribution of these certifications, as there is little centralised reporting.

Tracking progress

In 2012, industrial energy use increased slightly, reaching 143 exajoules (EJ), despite a decrease in overall industry energy intensity. To meet 2DS targets, energy use must be reduced by 0.9% per year and direct CO_2 emissions by 1.3% per year between now and 2025, compared with the current trajectory.

Recommended actions

To reach the 2DS, government and industry need to join forces to promote BATs and best practices, as well as to demonstrate and deploy new technologies. Energy-intensive industry is particularly exposed to impacts on competitiveness. Carbon leakage – the transfer of production to jurisdictions with less-strict emissions standards – is also a concern. In addition, technical constraints can slow down the process of implementing new technologies. Policy frameworks and support mechanisms should take these issues into consideration by creating long-term policy and energy price stability, removing energy subsidies, and coordinating internationally to avoid carbon leakage while promoting technology transfer and capacity building for BATs.

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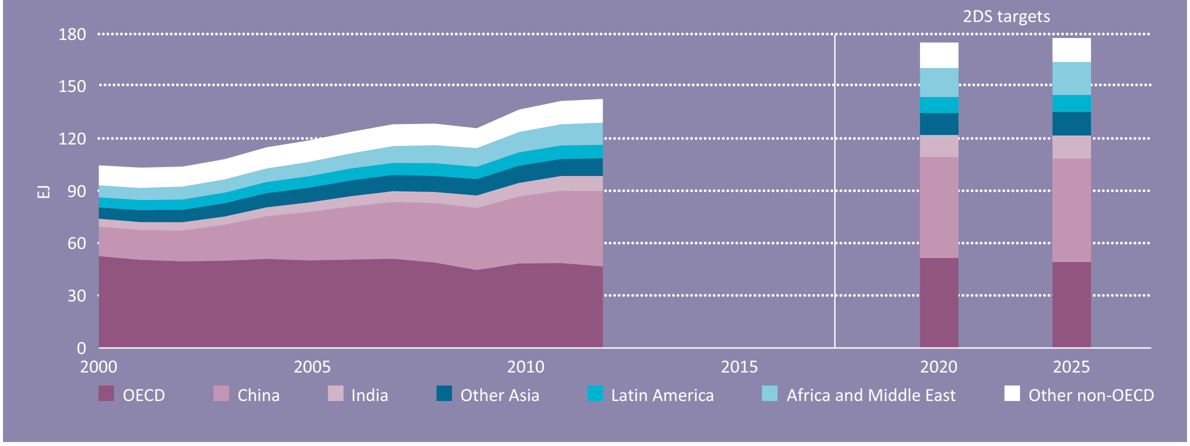
[4] Industry energy use data includes feedstock use in the chemicals and petrochemicals sector, and blast furnaces and coke ovens in the iron and steel sector.

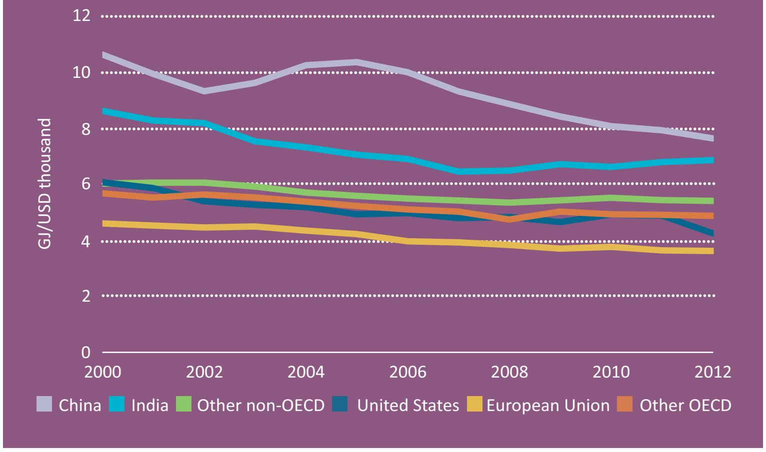
[5] The five major energy use sectors referred to by the State Council are iron and steel, cement, aluminium, plate glass, and shipping.

[6] ISO 50001 is an international standard for energy management systems that supports more efficient energy use in all sectors.

2.21 Global industrial energy use



2.22 Aggregated industrial energy intensity



7 345

SITES ARE NOW ENERGY MANAGEMENT STANDARD ISO 50001 CERTIFIED IN 70 COUNTRIES (91% IN OECD)

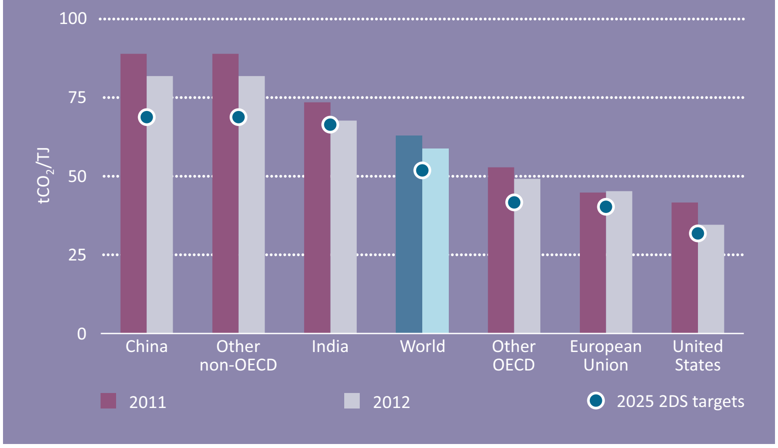
IN 2012 TOTAL INDUSTRIAL ENERGY USE INCREASED BY

1%

DIRECT CO$_2$ EMISSIONS DECREASED BY

6%

2.23 Aggregated industrial CO$_2$ intensity



For sources and notes see page 133

Iron and steel

● Improvement needed

~ Limited developments

The iron and steel sector has the second-largest energy consumption of all industrial sectors, (after chemicals and petrochemicals), accounting for 22% of total industrial energy use and 31% of industrial direct CO_2 emissions in 2012. The sector's energy use grew by 2.2% in 2012, partly because crude steel production rose by 1.4%. The 2DS requires growth in energy use of no more than 1.1% a year on average to 2025, even though crude steel production is expected to grow by almost 2% per year.

Recent trends

Global aggregated energy intensity in the iron and steel industry remained static. In 2012, the world average remained at 20.7 gigajoules per tonne (GJ/t), as in 2011, 5% lower than 2000 levels. The sector's energy intensity decreased by 1% to 14.3 GJ/t in OECD countries, but increased by 2% to 27.0 GJ/t in India, and by 5% to 25.4 GJ/t in other OECD non-member economies. Benefits of introducing more efficient production capacity have been offset by a decline in recycling as a share of total crude steel production, because the availability of scrap was unable to meet rapidly increasing crude steel demand. The steel industry in Europe has also been affected by overcapacity because of the recent slowdown in growth of demand (McKinsey and Company, 2013).

Production is expected to continue to grow steadily, so energy efficiency will need to be improved to meet the 2DS emissions target, through measures such as optimising the use of available energy embedded in process streams, deploying direct low-carbon process routes, and demonstrating and deploying innovative process technologies. The electric arc furnace (EAF) route, which is based on production from scrap and is less energy- and carbon-intensive than the basic oxygen furnace (BOF) method, represents 42% of crude steel production in 2025 in the 2DS, compared with 30% in 2012, though deployment is limited by scrap availability.

Several technologies that are at various stages of research, development, demonstration and deployment (RDD&D) focus on improving the energy and environmental performance of existing production routes, by enhancing process integration, optimising the use of process gas streams and facilitating carbon capture. However, progress is threatened by lack of resources and by economic and policy uncertainty. In the short term, the use of CO_2 capture in direct reduced iron (DRI) and smelting reduction processes could reduce emissions by 48 $MtCO_2$ by 2025 if coupled with permanent CO_2 storage.

Diffusion of ISO 14404, a standard on measurement of CO_2 emissions intensity in the iron and steel sector, has been increasing. The standard, adapted for both BOF and EAF, provides guidelines on measuring a steel plant's baseline emissions, allowing comparisons among plants and evaluation of the effects on emissions intensity of changes in operation or equipment. If widely adopted, such performance measurement or benchmarking programmes would also ensure that reported data are calculated on a similar basis.

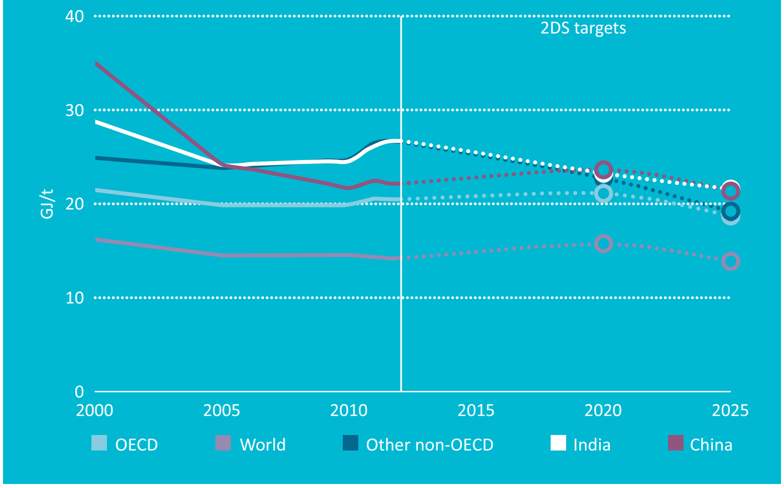
Tracking progress

Improvement is needed to put the iron and steel industry on a trajectory to meet 2DS targets. Overall growth in energy demand must be limited to 28% below the projected levels of current trends in the 2DS to 2025 (average annual growth of 1.1% per year), even though crude steel production is expected to grow by 25% from 2012 levels (average annual growth of 2% per year).

Recommended actions

Government and industry should promote the widespread application of BATs to help overcome the challenges of slow capacity stock turnover, high abatement costs, fluctuation in raw material availability, carbon leakage and industrial competitiveness, in both advanced and emerging economies. Private and public sector collaboration for development and deployment of innovative technologies to reduce CO_2 emissions from the iron and steel-making process is also critical.

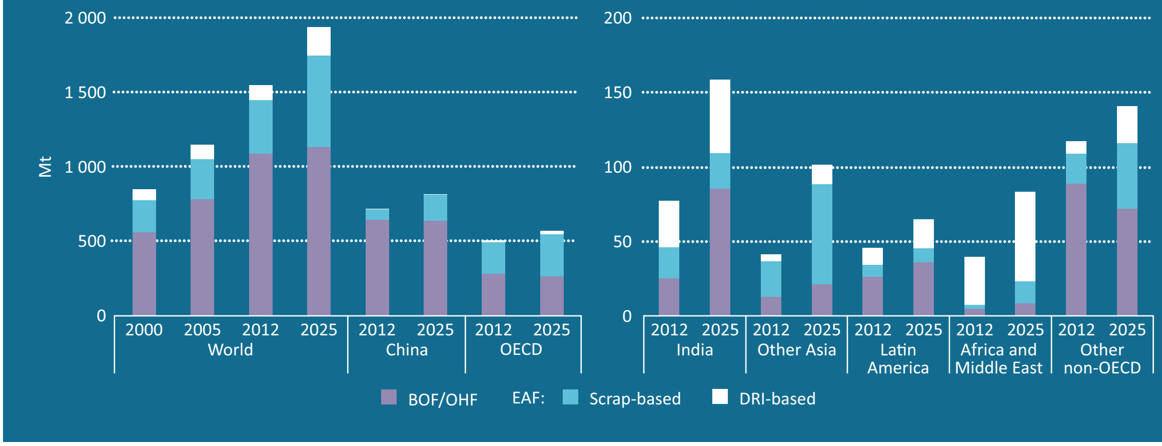
2.24 Aggregate energy intensity



30%

OF GLOBAL CRUDE STEEL PRODUCTION WAS BASED ON ELECTRIC ARC FURNACE IN 2012 (45% REQUIRED BY 2025 IN 2DS)

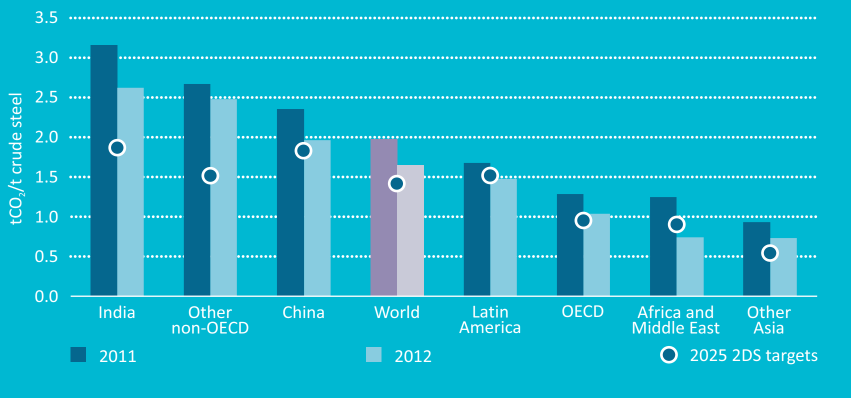
2.25 Crude steel production by process route



Recent developments

Limited availability of scrap, unable to keep up with crude steel demand, is constraining the deployment of more EAF

2.26 Direct CO_2 intensity



For sources and notes see page 133

Cement

● Improvement needed

~ Limited developments

In 2012, the cement sector accounted for 8.5% of total industrial energy use and 34% of industrial direct CO_2 emissions. While the sector has made steady improvements in energy intensity, to meet the 2DS energy use must decline by 0.2% per year through to 2025, and CO_2 emissions must be 12% lower than projected levels based on current trends in 2025, despite production growth of 17%.

Recent trends

In 2012, energy use in the cement sector reached 11.1 EJ, an increase of 4.8% from 2011, while global cement production increased by 200 Mt (5.5%). The majority of the increases in production were in China (up 5% in 2012), India (up 13% in 2012) and other developing Asian countries, while in Europe production decreased by 10%.

Global average thermal energy intensity of clinker production stayed at 3.7 GJ/t clinker in 2012. There was widespread progress in reducing the electricity intensity of cement production. The global average fell by 2% to 96.3 kWh/t cement, going beyond projected improvements from *ETP 2014*. Globally, these trends are expected to continue as more capacity is shifted to BATs. Depending on local energy prices and context, the thermal intensity of dry-process kilns could be almost half that of wet-process kilns, offsetting the higher investment requirements of this type of kiln (additional USD 57 million/Mt clinker capacity).[7] Shifting capacity towards dry-process kilns with six-stage preheaters and precalciners (BAT), while improving efficiency, reduces thermal intensity to 3.1 GJ/t clinker by 2025 in the 2DS.

Improvements from technology switching will not reduce emissions enough to reach 2DS targets. Increased use of alternative fuels, waste heat recovery systems and clinker substitution can help reduce emissions in the short term, though the trade-offs between use of alternative fuels or materials and energy efficiency should be considered. Bringing CCS technologies to commercial scale in the short term, with construction beginning within a decade, is critical to reducing direct emissions from cement manufacturing in the longer term. Process emissions make up a large proportion of the CO_2 emitted in cement production, and these can be reduced only through innovative products and processes relying on different feedstocks, or through CCS. Different CO_2 capture technologies have been pilot-tested in the cement sector but not yet demonstrated at commercial scale. Though these technologies are still not commercially viable, the 2DS sees first projects coming on line in 2025, capturing 0.5 $MtCO_2$, followed by further deployment in 2030.

Tracking progress

Improvement is needed to meet the 2025 2DS targets, especially as cement production is expected to grow by 1.3% per year through to 2025. Overall energy consumption must decline by 0.2% per year on average and emissions by almost 1% per year. Therefore, improvements in energy intensity and fuel switching are required in the sector to meet the target.

Recommended actions

Government and industry need to support RD&D programmes to bring to technical and commercial maturity new low-carbon technologies, as well as technologies that enable the use of low-quality feedstock, and to demonstrate and deploy emerging energy- and emissions-saving technologies, including CCS. Better data on cost and performance of CO_2 capture technologies will be critical for investment decisions, along with performance indicators for new products and processes, including advanced and low-carbon cement products. Simultaneously, strategies must be developed to address carbon leakage and industrial competitiveness concerns, while considering life-cycle approaches to emissions reduction.

Policies need to be developed to promote co-processing of alternative fuels, such as biofuels and waste, and to improve social acceptance of alternative fuels co-firing, particularly in regions where co-processing is currently low. Research is needed on operational health and safety risks of these alternative fuels.

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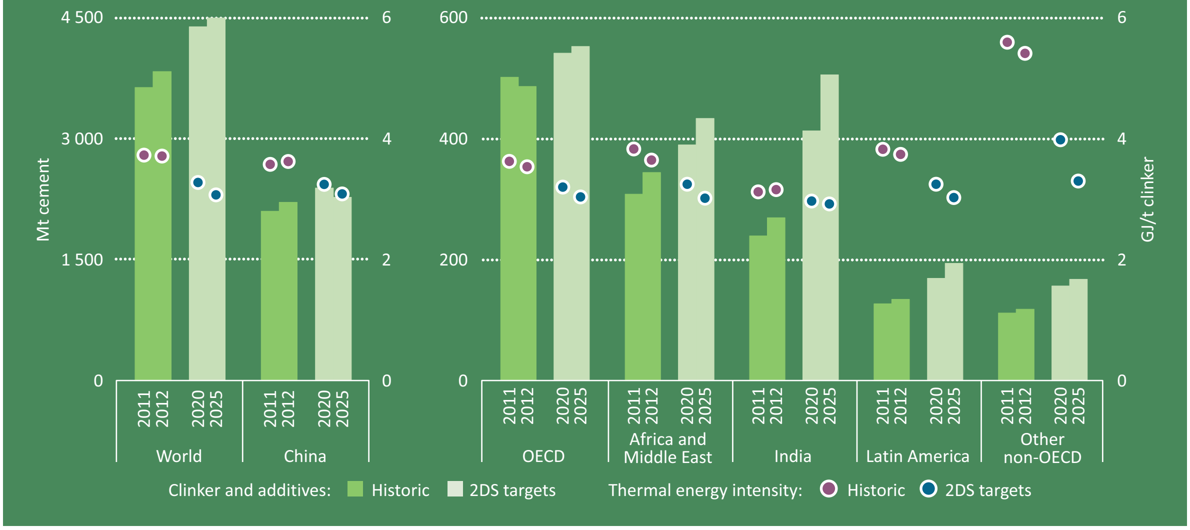
[7] Difference between capital expenditure on a typical wet-process kiln and on a dry-process kiln with four-stage preheater and precalciner.

2.27 Global production and thermal energy intensity



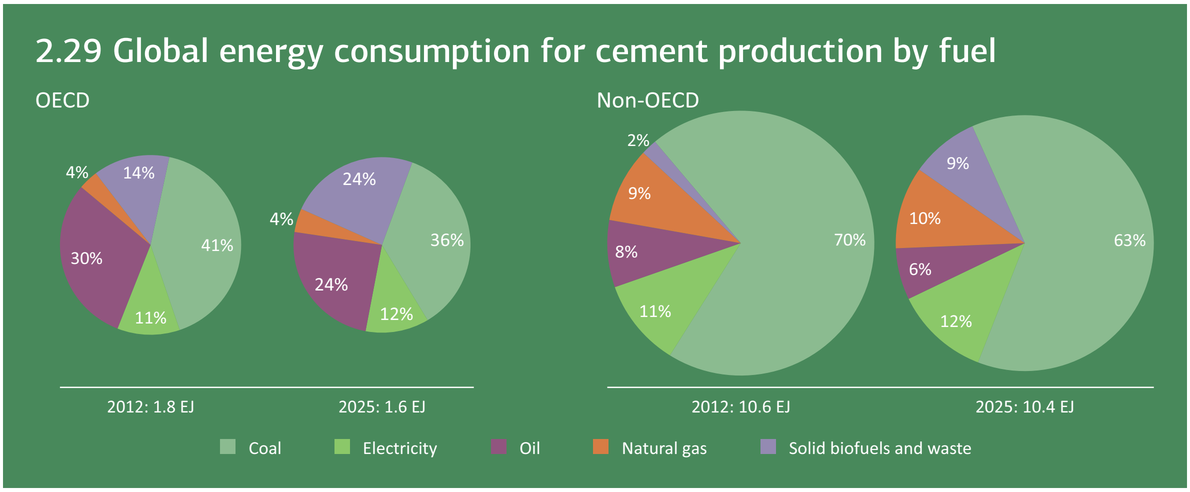
2.28 Key indicators in the cement sector

2DS low-demand variant	2011	2012	2020	2025
Cement production	3 635	3 836	4 394	4 506
Thermal energy intensity (GJ/t clinker)	3.7	3.7	3.3	3.1
Electricity intensity (kWh/t cement)	98.5	96.3	88.5	88.2
Share of alternative fuels and solid biofuels	5%	3%	8%	10%
Clinker to cement ratio	0.69	0.69	0.68	0.68
CO_2 intensity (tCO_2/t cement)	0.59	0.60	0.56	0.54

64%

OF CEMENT SECTOR DIRECT CO_2 EMISSIONS WERE PROCESS EMISSIONS IN 2012

2.29 Global energy consumption for cement production by fuel



For sources and notes see page 133

Transport

● Improvement needed

~ Limited developments

Global energy consumption by transport has grown by 2% per year since 2000 and accounted for 28% of overall energy consumption in 2012, or 105 EJ. Transport also led to emissions of 8.7 gigatonnes of CO_2 ($GtCO_2$)[8] in 2012. In the 2DS, transport energy demand needs to fall below 100 EJ by 2050, and CO_2 emissions from transport need to decline to 5.7 Gt.

Recent trends

Passenger transport accounts for nearly 60% of total transport energy demand, and 60% of this is in OECD member countries. Energy demand for freight transport was more evenly shared between OECD (47%) and OECD non-member economies (53%). Energy use in aviation remained close to 18% of the total needed for passenger transport across the past decade, both in OECD and OECD non-member economies.

Transport is the least diversified energy end use: oil products account for 93% of final energy consumption in 2012, followed by biofuels at 2%, a sixfold increase since 2000. Most of the natural gas used for transportation (about 2% of the total energy demand) is for pipeline transport, but natural gas use in other transport modes has experienced a tenfold increase since 2000, to more than 1% of total transport fuel use in 2012. The bulk of this growth took place in OECD non-member economies, representing 90% of the natural gas demand that was not used for pipeline transport.

In 2012 passenger cars accounted for 77% of passenger transport energy use in OECD member countries and 56% in OECD non-member economies; even though new vehicle registrations in OECD non-member economies now exceed those in OECD member countries (OICA, 2014), the vehicle fleet and the share of energy used by passenger cars in the non-OECD remained lower than in the OECD in 2012. Public transport modes (road and rail) represented 4% of the total transport energy demand in the OECD and 17% in the non-OECD. The lower energy intensity per passenger kilometre of public transport modes, however, translated into a higher share of transport activity (expressed in passenger kilometres): 15% in OECD and 52% in OECD non-member economies.

Road, the most energy-intensive freight transport mode besides aviation, represented 67% of the total energy used to move goods. Trucks consumed nearly three-quarters of this, with the remaining quarter mostly used by light commercial vehicles (LCVs). Trucking activity (in absolute terms) was more relevant in OECD non-member economies than in the OECD, while LCVs moved a comparable amount of goods in each of these regions. The second-most-important freight transport mode for energy demand (23%) is shipping, including both domestic and international navigation. Maritime transport takes the lion's share in this portion. Its low energy intensity, however, is such that maritime transport is by far the most relevant mode in terms of activity: 77% of total tonne kilometres in 2012. Rail freight is especially relevant in regions such as North America and continental Asia where long-distance water transport is not viable. Globally, it accounts for 4% of energy demand for freight transport and 13% of total tonne kilometres.

Tracking progress

Transport energy and CO_2 emissions have increased by 28% since 2000, or 2% per year. The sector is not on track to meet 2DS targets. Stark changes to the trends of the last decade are required: energy demand needs to stabilise at least, while CO_2 emissions need to fall.

Recommended actions

Getting transportation on track to meet 2DS targets requires implementing a broad set of policies, summed up as "Avoid, Shift, Improve". These measures also enable reductions in air pollution, road fatalities and congestion, while improving passenger and freight transport access: avoiding unnecessary transport activity, for example by using land-use planning to favour compact urban forms, and ICTs to lower the need for traveling; shifting travel to energy-efficient modes, for example by providing adequate public transport infrastructure; improving the specific fuel consumption of vehicles (e.g. via fuel economy standards), their capacity to handle energy diversification (e.g. with incentives for multi-fuel vehicles), and the characteristics of fuels (e.g. with quality specifications to improve the carbon intensity of fuels).

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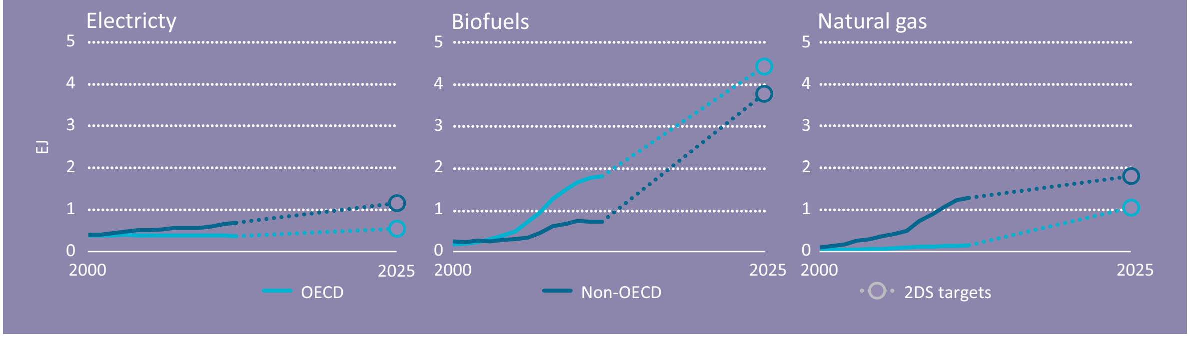
[8] Expressed on a well-to-wheel basis.

2.30 Alternative transport fuels

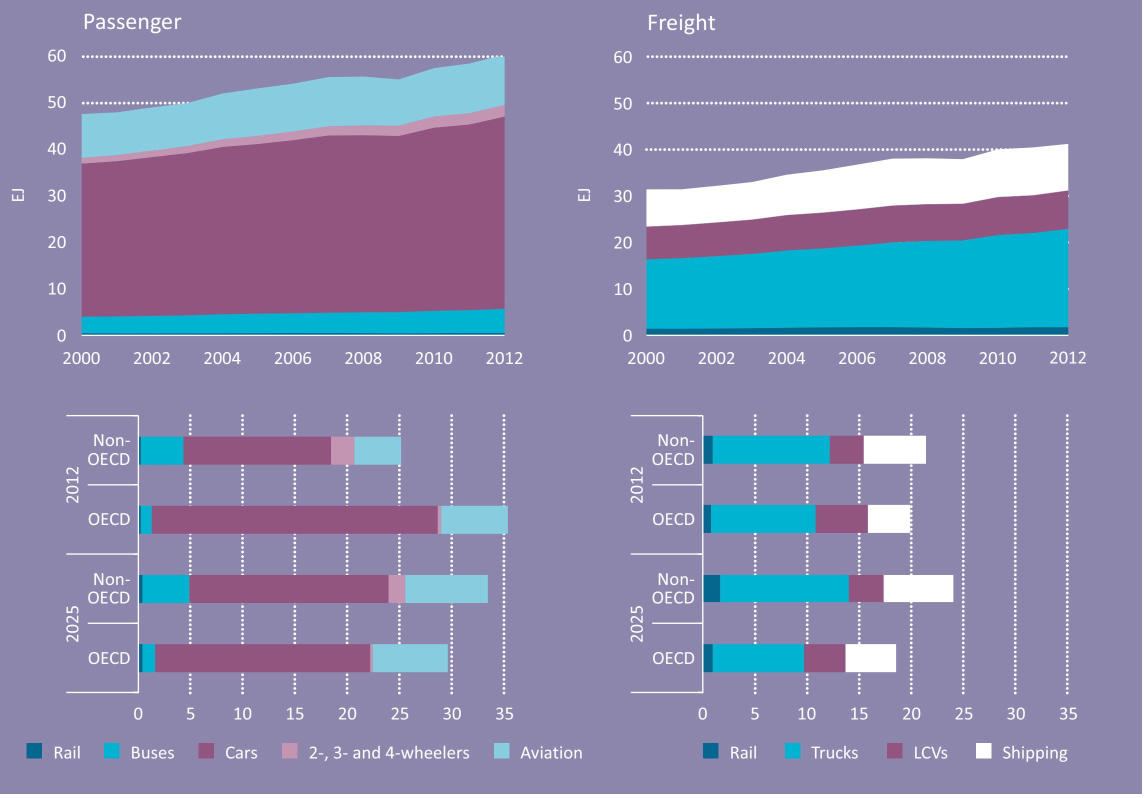


Once energy, infrastructure, congestion, environmental and health-related social costs are taken into account, public transport modes used for urban mobility deliver net savings compared to individual vehicles

50% of the cost of public transport systems of European cities is covered by subsidies

10% drop in the public transport mode share in total passenger kilometres in OECD non-member economies since 2000

2.31 Passenger and freight transport development



For sources and notes see page 133

Fuel economy

● Improvement needed
↗ Positive developments

To reach the 2DS target of halving specific fuel consumption of new conventional fuel PLDVs by 2030, global improvement rates of 3% per year have to be achieved. OECD countries have almost achieved this rate, partly due to strong policy measures, but progress has stagnated in OECD non-member economies because of a trend towards bigger, more powerful cars.

Recent trends

Many OECD markets, as well as large developing economies, have already introduced fuel economy regulations for road transport vehicles, in order to direct existing technological potential towards enabling fuel savings rather than enhancing vehicle performance. Several important and fast-growing markets in Asia, Latin America, the Middle East and Africa have not yet regulated fuel economy for transport vehicles, and the policy coverage is uneven across transport modes.

Almost all OECD member countries and China, the largest single-country market, have adopted policy measures to improve fuel economy of new PLDVs.[9] In 2012, the United States announced the extension to 2025 of the current regulatory framework, as well as a substantial improvement in average vehicle fuel economy targets. In the same year, Brazil implemented fiscal instruments promoting environmentally friendly innovations. Mexico introduced fuel economy standards in 2013. India and Saudi Arabia did so in 2014. Almost 80% of the global PLDV market is now regulated.

Fuel economy regulations have not been as widely adopted for heavy-duty vehicles as they have for PLDVs. Japan established the world's first fuel economy programme for medium- and heavy-duty vehicles in 2005 and will enforce it in 2015. China introduced heavy-duty fuel economy regulations in 2011, with a second phase starting in 2014/15. Canada and the United States introduced regulatory measures on heavy-duty road vehicles in 2014. Efforts are under way to develop similar regulations in the European Union, India, the Republic of Korea and Mexico.

Canada, the European Union, Japan, Mexico and the United States have also introduced fuel economy regulations for LCVs, building on their experience with PLDVs. China is the only country that has introduced fuel efficiency standards for motorcycles.

Tracking progress

For passenger cars, regions with regulations in place show annual improvement in fuel economy of around 2.6% since 2005. Non-regulated markets lag behind, mostly due to a shift of preference towards bigger and more powerful vehicles as consumers' personal income has increased. Globally, the average fuel economy of cars has improved by 2% per year since 2005, below the 3% per year needed to reach the 2DS efficiency target. Despite recent encouraging policy developments, further improvement is needed to meet the 2DS.

Recommended actions

Governments need to enlarge the coverage of fuel economy regulations, and strengthen the stringency of those already introduced, to meet 2DS emissions reduction targets.

A widening gap between tested and real fuel economy could neutralise much of the improvement delivered under testing conditions. Despite recent progress with the development of the Worldwide Harmonised Light Vehicle Test Procedure (WLTP), the gap between testing conditions and on-road results needs to be reduced still further. Parallel efforts should aim to include elements related with usage patterns in fuel economy regulations, as the higher mileages of larger and more powerful vehicles can contribute to the gap between on-road fuel consumption averages and tested results.

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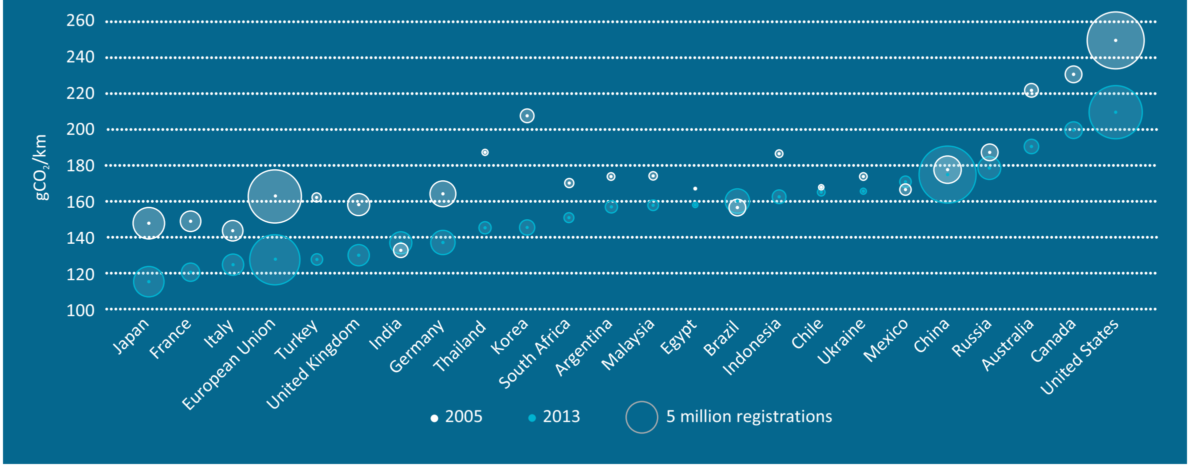
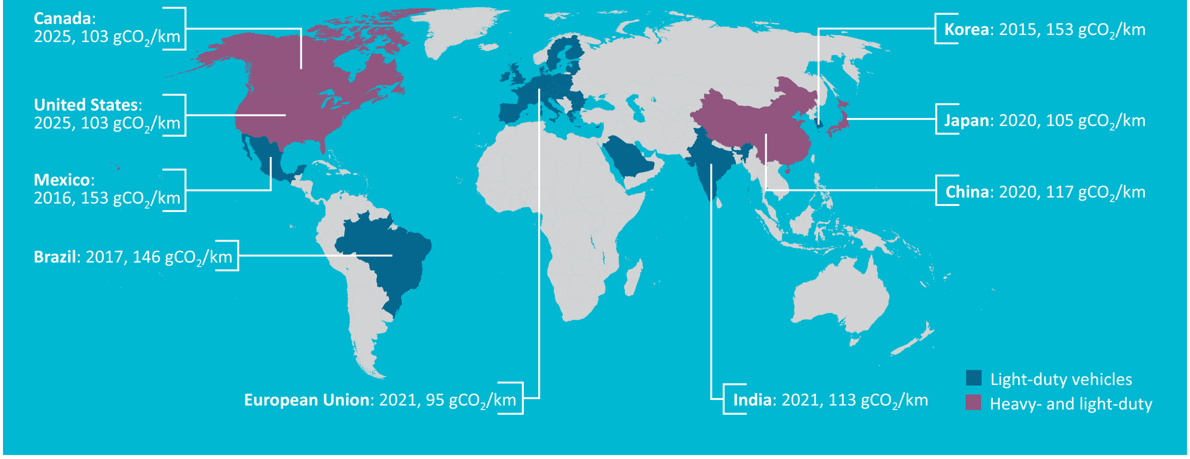
[9] Such as fuel economy standards, CO_2-based taxation, rebate or feebate systems (i.e. the combined use of taxation and subsidies to promote innovative technologies or support consumers and manufacturers opting for environmentally friendly vehicles) and labelling schemes.

2.32 New PLDV tested fuel economy



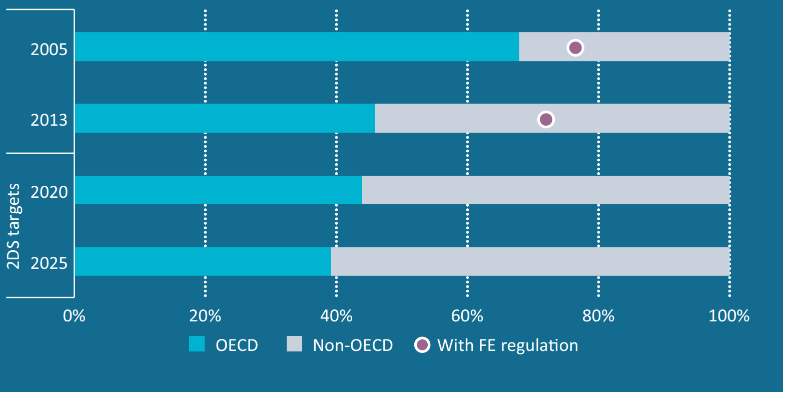
2.33 New vehicle fuel economy standards



30%

DISCREPANCY BETWEEN TESTED VEHICLE FUEL ECONOMY AND REAL ON-ROAD FUEL ECONOMY

2.34 Global PLDV market



For sources and notes see page 133

Electric vehicles

● Improvement needed
↗ Positive developments

Global sales of light-duty passenger electric vehicles (EVs)[10] grew about 50% from 2013 to 2014, a slowdown compared with previous years, but encouraging growth in absolute numbers starting from a small base. Sales of PHEVs grew 57% and BEVs grew 43% from 2013 to 2014. Battery costs continued to fall and vehicle range increased for several second-generation EV models, but greater government spending is needed to drive substantial deployment to meet ambitious 2DS targets.

Recent trends

While more EV models were released to the market, and global sales of PHEVs and BEVs grew from 2013 to 2014, there was otherwise a relative slowdown in government spending and EV deployment. Only in the Netherlands, Norway, Sweden, and the United States did sales of EVs exceed market shares of 1%. The cumulative global stock grew to about 665 000 EVs, impressive considering there were almost none on the road in 2009, but the Electric Vehicles Initiative (EVI) cumulative government target of 20 million EVs on the road by 2020 will be hard to achieve without much faster growth. After a slow start since the introduction of mass market EVs in 2010, sales of EVs in China finally took off, growing from around 13 000 in 2013 to more than 80 000 EVs in 2014.

EV charging infrastructure grew from around 46 000 slow chargers (Level 1 and 2) in 2012 to around 940 000 in 2014. The numbers of fast chargers (Level 3, CHAdeMo, and SuperCharger) grew from 1 900 to 15 000. Some car manufacturers began to sell vehicle-to-home systems, enabling customers to use vehicles to charge homes as well as vice versa; these are particularly suited to solar PV-powered homes.

EVI's 2015 update of its *Global EV Outlook* (IEA, 2015) shows battery costs continuing to decrease. However, battery costs have yet to achieve first-cost parity with equivalent internal combustion vehicles (versus lifetime-cost parity, already achieved for many models). More RD&D funding is needed to reach lower battery cost targets by 2020, which would increase the competitiveness of EVs not only on the basis of purchase cost but also by decreasing the cost of extending vehicle range.

Electric 2-wheelers make up the largest electrified vehicle fleet in the world, with over 230 million electric 2-wheelers in China alone. The total stock outside China is currently substantially smaller at approximately 5 million, but sales are increasing. Electric buses are increasingly being considered by cities as a way of reducing local air pollution; there are currently 46 000 electric buses worldwide, with 36 500 in China alone. Passenger vehicles have enjoyed trickle-down innovations from motorsports for years. In 2014 this extended to EVs with the launch of the all-electric racing series Formula E, which started in Beijing and will finish its inaugural circuit in London in 2015.

Tracking progress

Annual average growth of 80% in EV sales to 2025 is needed to meet 2DS targets, so improvement is needed, as growth is currently 50% per year. While there were many policy discussions in 2014 on vehicle electrification, few government actions were taken to support deployment. A slowdown in spending hampered progress, while incentives and infrastructure deployment remained otherwise unchanged.

Recommended actions

Support for RD&D continues to be crucial. To achieve 2DS deployment targets for 2020 and beyond, governments need to bolster RD&D to ensure EVs have longer driving range with less costly batteries.

Vehicle electrification needs to be considered from a broader perspective than just electric passenger vehicles, as increased usage can make a multi-modal approach viable – using ICT, for example, to integrate electric buses, 2-wheelers and rail with passenger cars.

Governments should support cities and regions to develop sustainable business models underpinning EV infrastructure.

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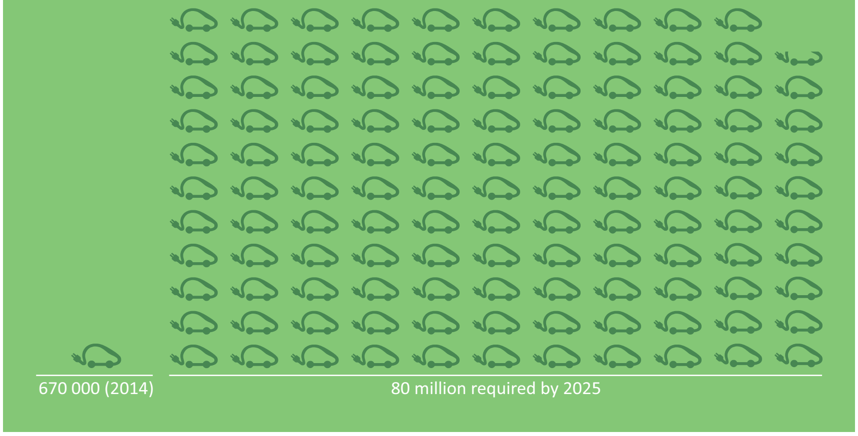
[10] Including plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs).

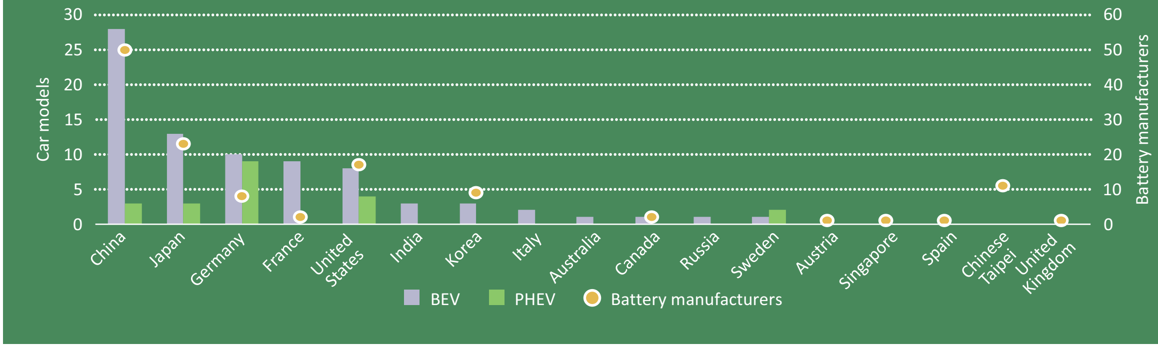
2.35 Global electric vehicles stock



4

COUNTRIES HAVE EV SALES SHARES OVER 1% OF TOTAL NEW CAR SALES

2.36 EV models available by country and lithium-ion battery manufacturers



OF EV SALES

91%

ARE BEVS IN NORWAY

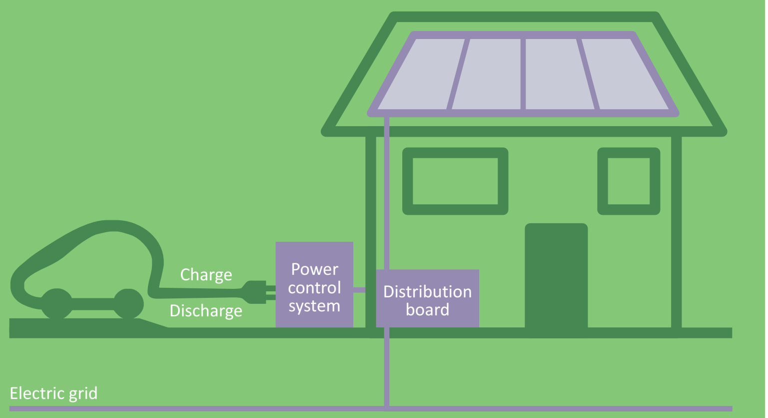
82%

ARE PHEVS IN THE NETHERLANDS

49%

ARE PHEVS IN THE UNITED STATES

2.37 Vehicle-to-home system



For sources and notes see page 133

Buildings energy efficiency

● Not on track
~ Limited developments

Globally, buildings accounted for 32% (118.6 EJ) of final energy consumption in 2012, and 53% of global electricity consumption. Despite numerous studies highlighting untapped energy efficiency opportunities, that can reduce carbon emissions without increased life-cycle costs, progress has been inadequate to achieve 2DS targets by 2025.

Recent trends

Despite the continuing importance of energy efficiency in buildings, overall financial support and policy priority are widely believed to have peaked a few years ago, whereas a sustained effort is needed to overcome the major market barriers. Several developed countries have been pursuing zero-energy buildings (ZEB) for at least a decade. Outside the European Union, however, progress has been very slow, mostly because energy prices have remained low and RD&D has not yet resulted in widely available lower-cost technologies. Even in the European Union, where mandatory directives require member states to pursue NZEBs by 2020, many policy experts are sceptical that the ambitious target dates will be achieved (IEAi, 2014). The number of buildings achieving very low energy consumption or NZEBs is small. Actual performance or energy consumption is not being adequately tracked, and nor is NZEBs' share of new construction. Policy makers need to make energy efficient buildings a priority and take steps to improve progress, such as a major effort on public buildings.

The spread of mandatory building codes and more stringent energy requirements shows that progress continues in most of the world, but it is too slow. A lack of testing and rating protocols (for components and for whole buildings), poor product availability, low education and knowledge, and limited investment in advanced construction have prevented regulators from enacting and enforcing stringent building codes. The European Union, which has made the most progress, requires member countries to include cost optimality as a criterion when developing building codes. France, for example, has enacted a building code that limits space heating, water heating, cooling and lighting energy to 180 megajoules per square metre (50 kilowatt hours per square metre [kWh/m^2]) or less.[11] Implementation is just beginning, however, and researchers expect compliance to remain low for some time.

Deep energy renovation of at least 1% to 2% of existing buildings per year has been recommended as a key policy by stakeholders and the IEA for some time.[12] The technical and economic benefits have been demonstrated by case studies in a wide range of climates and regions. The European Union is the only region that seems to be pursuing this policy, and with a high space heating requirement, large gas demand, and recent concerns about gas supply security, it is possible this priority will be further elevated by policy makers. It does appear to be of higher interest in the United States for government buildings, but activity is limited to a few buildings from a research perspective rather than a deployment focus.

Tracking progress

Final energy consumption in buildings increased by 1.5% per year between 2000 and 2012. The rate has not declined despite recent reduced global economic growth. To achieve 2DS targets, it should not grow by more than 0.7% per year through to 2025. As global economic prosperity returns and the world's population grows by 1 billion people by 2025, however, there is a serious risk that buildings' energy consumption will continue to grow at a high rate (1.4% per year), reaching 142.7 EJ.

Recommended actions

IEA member countries should develop and promote deep energy renovation as part of normal refurbishment and limit financial incentives to very high-performance buildings (systems and components). The quality of energy performance certificates needs to improve in EU member countries, and the use of such certificates needs to spread to all regions of the world, with more effort to make them more effective (BPIE, 2014). All governments – especially in emerging economies – need to make greater efforts to develop, promote and enforce more stringent building codes, with the eventual goal of ZEBs.

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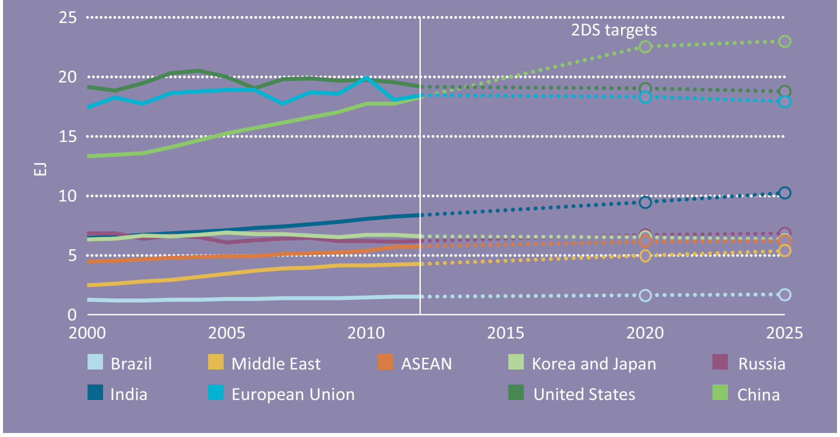
[11] The building code allows scaling based on building type and climatic region.

[12] Where deep energy renovation or retrofit is defined as a reduction in energy consumption of at least 50% or to not more than 60 kWh/m^2 for building code loads (e.g. space conditioning, water heating and hardwired lighting), (GBPN, 2013).

2.38 Energy consumption in the buildings sector

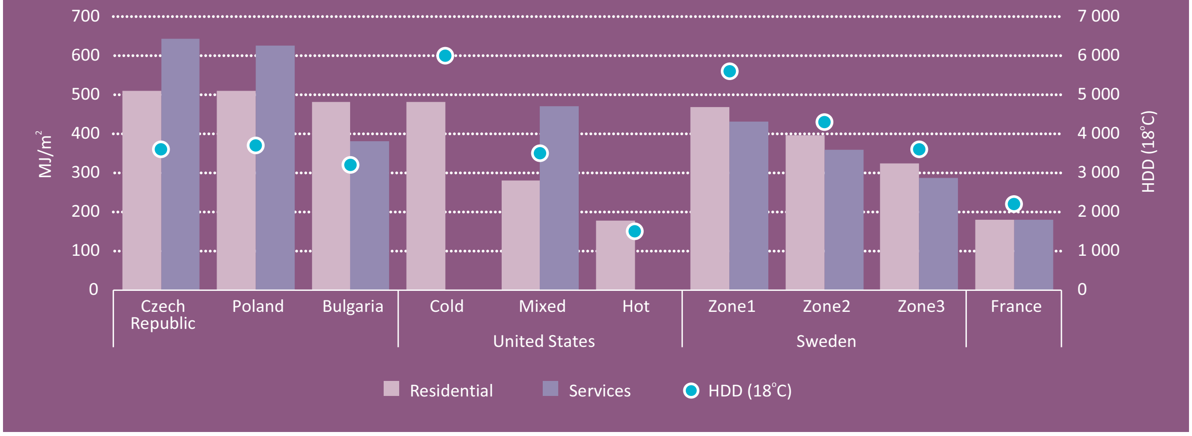


THE 2DS TARGET FOR 2025 ALLOWS FOR ENERGY DEMAND GROWTH BUT ONLY AT

50%

OF THE CURRENT GROWTH RATE

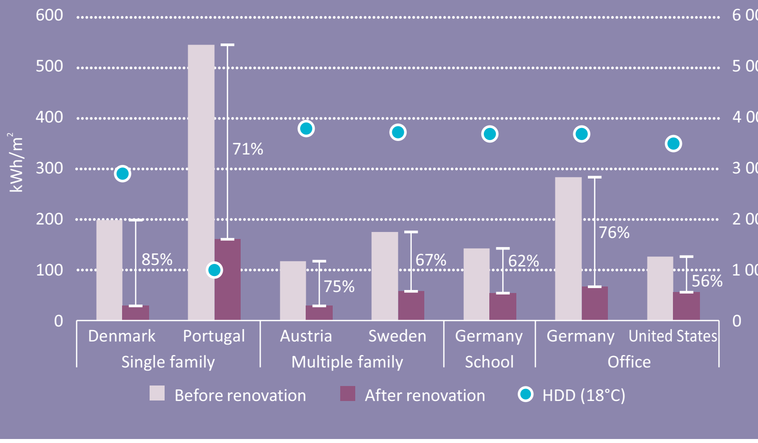
2.39 Building code energy intensity



Policy recommendation

To encourage investment in high-performance buildings, all countries should develop and promote building performance metrics that are compatible with financing organisations, including multiple benefits beyond energy efficiency

2.40 Deep renovation case studies



For sources and notes see page 133

Building envelopes

🔴 Not on track

~ Limited developments

Energy use by space heating, cooling and lighting, which represents 38% of global buildings energy consumption, could be reduced by more than half by ensuring that building envelopes are energy efficient. Advanced building envelope materials and integrated construction techniques enable the construction and renovation of buildings that consume little or no energy.

Recent trends

Windows are responsible for the highest heat loss in winter and highest heat gain in summer per unit area in the majority of buildings in the world. In moderate and cold climates, advanced windows can provide a positive net energy contribution when combined with highly insulating properties and dynamic solar control, and are viable today in places with high energy prices (IEA, 2013b). All areas of the world should require double-glazed, low-emissivity (low-e) coated windows (with climate "optimised" solar control) with low conductive frames. Cold climates should move to even higher-performing windows with low thermal transmittance (U values < 1.1 watts per square metres Kelvin [W/m^{2}K]) that effectively add a third low-e glazing or include vacuum glazing technology. Advanced windows offer systems benefits beyond efficiency, such as elimination of perimeter zone conditioning, improved comfort and reduction in equipment capacities. Progress in commercialising advanced windows has been too slow in all but a few EU countries; global market share is in the single digits. Voluntary energy efficiency labelling programmes in the United States (ENERGY STAR) and several EU countries (e.g. France and United Kingdom) specify criteria that are too weak for cold climates.[13]

If insulation is properly installed at optimal levels during planned building construction or renovation, it can be one of the most cost-effective energy efficiency measures. Insulation is available in most regions of the world and is usually installed in many high-profile buildings. It is typically installed at well below optimal levels, however, which are highly dependent upon local and regional conditions, including climate, cost of materials and energy prices. More effort is needed, including mandatory building codes, to ensure more widespread installation of higher levels of insulation (achieving low U values), which can also occur as independent retrofit measures.

Effective air sealing can reduce heating and cooling energy by 20% to 30% and needs to be implemented as part of any construction and renovation project. Air leakage rates are often determined as part of a quality energy audit or building performance rating and labelling activity. However, the vast majority of EU performance certificates do not require mandatory air leakage validated tests. While new construction in the most mature markets includes air sealing (low air leakage), the majority of existing buildings have high air leakage. More effort is needed globally to ensure that any building that will be heated or cooled is properly sealed. When sealing is done correctly, with controlled ventilation and advanced heat recovery, it can improve indoor air quality.

Tracking progress

Overall progress on efficient construction techniques – including optimal levels of insulation, well-insulated windows and proper air sealing – is too slow. Most regions of the world are not on track to realise the potential to reduce thermal loads in new buildings by 75% to 80% compared with loads in existing buildings.

Recommended actions

More policy activity needs to be focused on advanced building envelope materials and construction techniques, including awareness, education, building material test and rating protocols, building codes and financial incentives for very high-performing products and systems. Promoting building codes for insulation and windows with lower U values, along with mandatory air sealing are critical. Greater effort is needed to help establish commodity-based advanced building materials and products in emerging markets. A key policy should be for governments to specify proper building material requirements and codes during construction and renovation of public buildings. Data quality and tracking of efficient building materials and products are essential to ensure that advanced construction develops globally.

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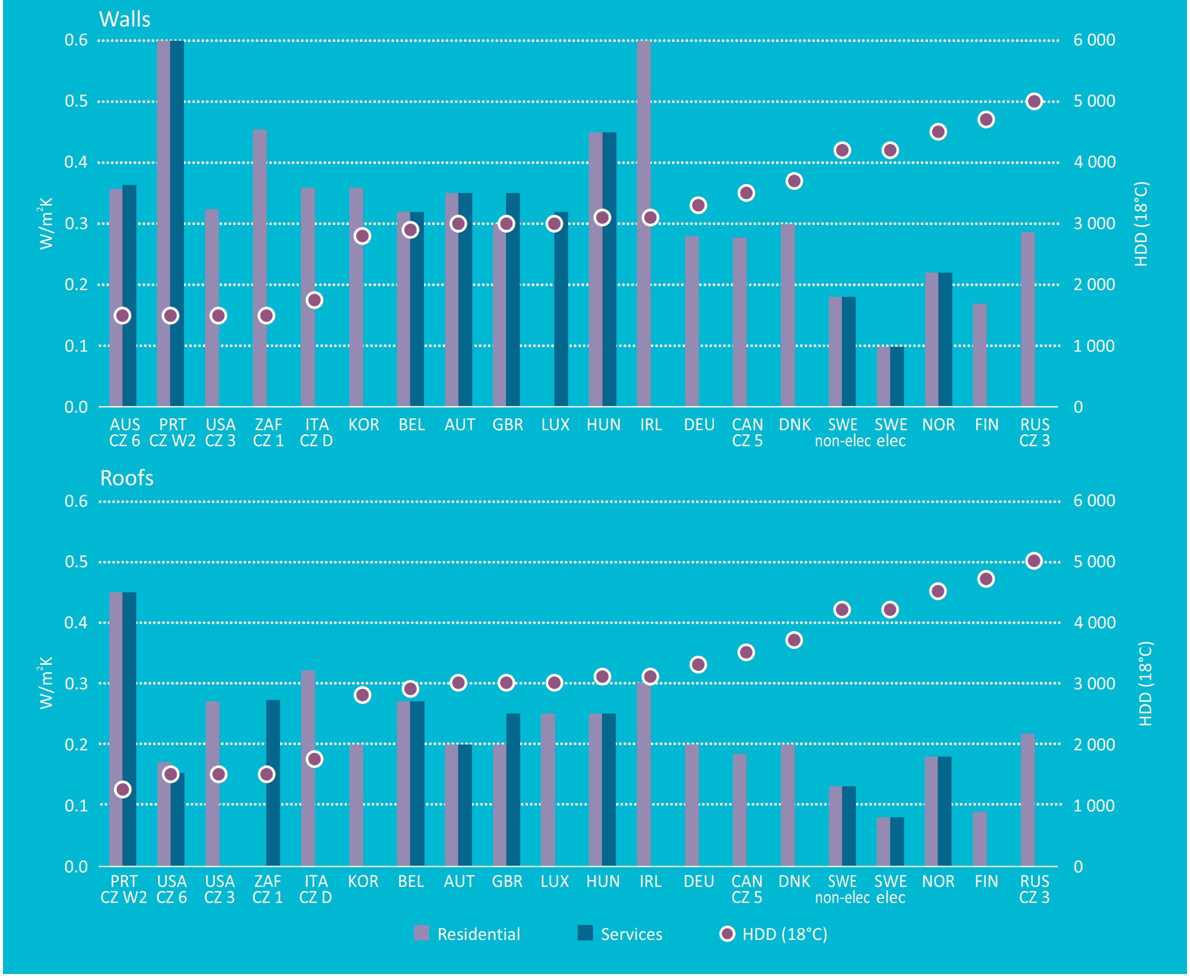
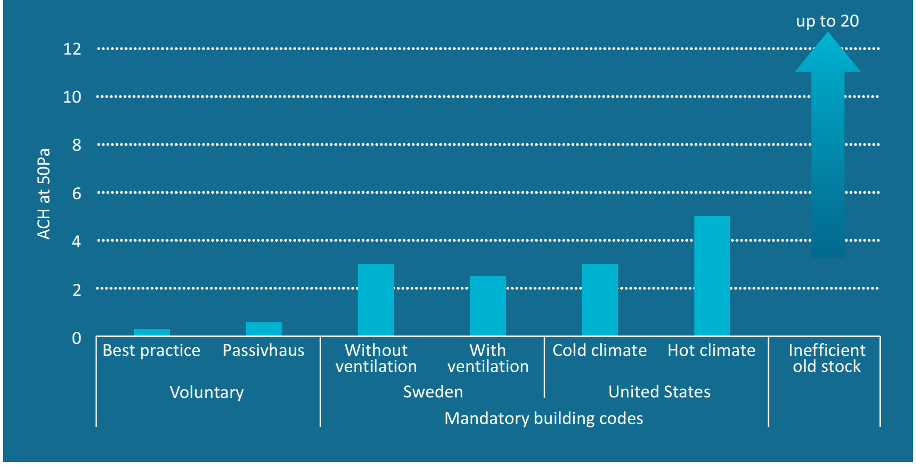
[13] New ENERGY STAR criteria effective January 2016 specify U values < 1.5 W/m^{2}K in cold climates, and France and the United Kingdom designate moderate performance windows being classified as A+ as part of its classification system. Many policy experts believe that A+ designations should be reserved for energy positive windows.

2.41 U values for walls and roofs



2.42 Air leakage rates



Key point

Beyond Canada, northern United States and north-western Europe, the majority of construction in the world uses sub-optimal products

For sources and notes see page 133

Appliances, lighting and equipment

● Improvement needed

~ Limited developments

Energy demand continues to grow for appliances, lighting, and a large array of electrical and fossil fuel-powered equipment, despite significant progress on labelling and mandatory minimum energy performance standards (MEPS). Market penetration of major appliances has increased significantly in emerging markets, and plug loads from electrical devices and network usage continue to grow in all markets, resulting in energy consumption growth of over 50% from 2000 to 2012.

Recent trends

The number of energy performance standards and labels has grown significantly worldwide, with over 3 600 measures identified (EES, 2014). The geographical concentration of such programmes has gradually shifted from the United States and the European Union towards Asian and other countries; China has 100 separate measures. However, greater alignment and collaboration is needed on standards of globally traded products.

The Super-efficient Equipment and Appliance Deployment (SEAD) Initiative quantified the annual energy savings in 2025 from 81 performance standards promulgated in 12 participating economies between 2010 and 2013.[14] This analysis finds that MEPS are expected to save 2.4 EJ by 2025. A further 12 EJ could be saved by 2030 with more assertive MEPS (SEAD, forthcoming). The majority of standards are applicable to electrical appliances but also include fossil fuel-powered equipment such as boilers and water heaters. Energy savings from efficiency standards are expected to reduce OECD residential electricity consumption by nearly 10% compared to current trends in 2025. Further research is needed to evaluate the savings potential for standards in China and other developing countries.

Energy efficiency regulations for lighting products have moved sales away from inefficient incandescent lamps, but towards halogen lamps rather than more efficient compact fluorescent lamps (CFLs) or light-emitting diode (LED) lamps (E4 IA, 2015). More assertive policies are needed to achieve large savings.

When MEPS are complemented by policies such as R&D, incentives, labelling, and educational programmes, the impact can be even more significant. For example, the European Union has promoted condensing boilers that are up to 17% more efficient than traditional boilers. Market conditioning has preceded MEPS that will come into force in September 2015. Japan has made significant progress in adopting heat pump water heaters (HPWHs) that use 75% to 50% less electricity than electric resistance technologies. As a result of R&D and incentives, sales in Japan are 20 to 40 times higher per capita than in the European Union and the United States. R&D has enabled the United States to bring the cost of HPWHs down to below USD 1 000; EU prices are typically over USD 3 000. Globally, around 25 million inefficient electric resistance storage water heaters continue to be sold each year. Overall, more integrated, comprehensive and stringent policies are needed for all product categories (IEA, 2013c).

Tracking progress

Despite recent progress in introducing MEPS, improvement is needed to meet 2DS targets. Electricity demand has increased by over 4% per year for the last decade, but this rate needs to fall to 1.2% in the 2DS.

Recommended actions

Much more effort is needed to promulgate more stringent MEPS globally, along with tracking and evaluation programmes, especially in emerging markets. Inefficient light bulbs, including halogens and electric resistance heaters, should be eliminated from the market and replaced with more efficient technology (e.g. CFLs, LEDs, HPWHs, heat pumps and solar thermal). IEA member countries need to transfer lessons learned to emerging markets, including capacity building related to analytical capability, stakeholder engagement, compliance monitoring and quality testing. More R&D and market conditioning is needed to bring down the cost of advanced technologies so they are commercially viable in areas with lower energy prices.

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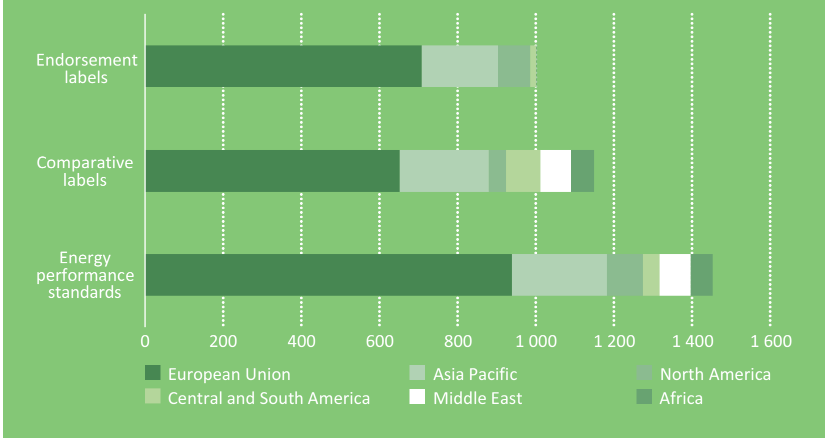
[14] SEAD economies analysed include Australia, Brazil, Canada, the European Union, India, Indonesia, Japan, Korea, Mexico, Russia, South Africa and the United States. For more information on SEAD, see superefficient.org.

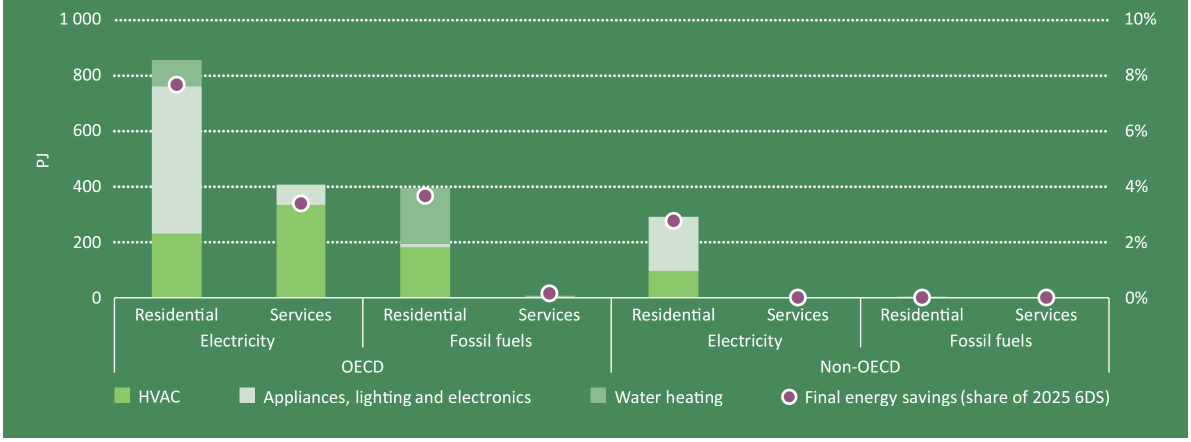
2.43 Appliance and equipment efficiency measures



80%

OF ENERGY CONSUMED BY SOME NETWORK-ENABLED DEVICES IS USED JUST TO MAINTAIN CONNECTIVITY

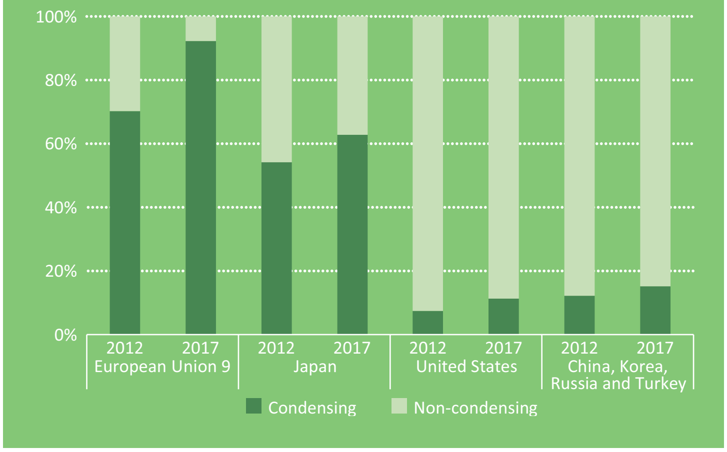
2.44 Mandatory appliance and equipment energy savings forecast



20%

INCREASE IN LIGHTING ENERGY CONSUMPTION BETWEEN 2000 AND 2012. IN THE 2DS TOTAL LIGHTING CONSUMPTION IN 2025 STABILISES AT JUST BELOW 2012 CONSUMPTION LEVELS.

2.45 Condensing boilers market share



For sources and notes see page 133

Co-generation and DHC

● Improvement needed

~ Limited developments

Despite an absolute increase in co-generation, it has plateaued as a share of global electricity generation.[15] Efficient DHC systems have not been extensively deployed, despite their potential to help create a more integrated energy system.

Recent trends

Modern co-generation and DHC systems are highly efficient and increase the flexibility of electricity and thermal grids, but these benefits have not been fully captured. In 2012, co-generation of heat and power had a global average efficiency of 58%, compared with 37% overall for conventional thermal power generation.[16]

Co-generation deployment on a global level has plateaued in recent years, decreasing slightly to 9% of global electricity in 2012. In absolute terms, electricity production from co-generation has grown moderately, to just over 1 000 TWh per year in OECD countries and nearly the same level in OECD non-member economies. In absolute terms, production of heat from co-generation units has increased steadily, reaching over 6.5 EJ globally in 2012, or 44% of global commercial heat production, with most of the growth in OECD countries.

Modern district cooling (DC) networks can achieve efficiencies five to ten times higher than traditional electricity-driven cooling systems.[17] Data on progress in DHC is limited, but the district heating (DH) market is much more developed than the DC market. Both are more advanced in Europe, where more than 5 000 DH systems are in operation, supplying more than 10% of European heat demand in 2012 (556 TWh), and DC accounts for about 2% of cooling demand (3 TWh) (DHC+ Technology Platform, 2012).

Micro-co-generation, which can be beneficial for individual buildings where DHC is not economical, has also become more prevalent. Korea is targeting additional small-scale co-generation capacity of up to 2.7 GW by 2017, and Japan aims to have 1.4 million units installed by 2020 (IEA, 2013d, 2013e, 2013f).

Tracking progress

Greater deployment of efficient and cost-effective co-generation and DHC is needed. While absolute co-generation has increased, its global share of electricity generation has not changed significantly over the past decade. DH represented 10.8% of global heating energy use in 2012. Co-generation and modern DHC systems can help reduce primary energy demand and increase overall system efficiency, and should be part of an integrated approach to meeting 2DS targets across all sectors.

Recommended actions

Policy makers should enable co-generation and DHC to compete with other technologies by removing barriers to interconnection, facilitating interconnection standards, and rewarding efficient operation and use of low-carbon energy sources. They should also address the high up-front costs, inflexible business structures and lack of long-term visibility on regulatory frameworks that also limit co-generation and DHC.

Strategic planning of local, regional and national heating and cooling should be developed to identify cost-effective opportunities to efficiently develop co-generation and expand DHC networks. Policy makers should also facilitate investment in modernising and improving existing DHC networks to make them more energy efficient.

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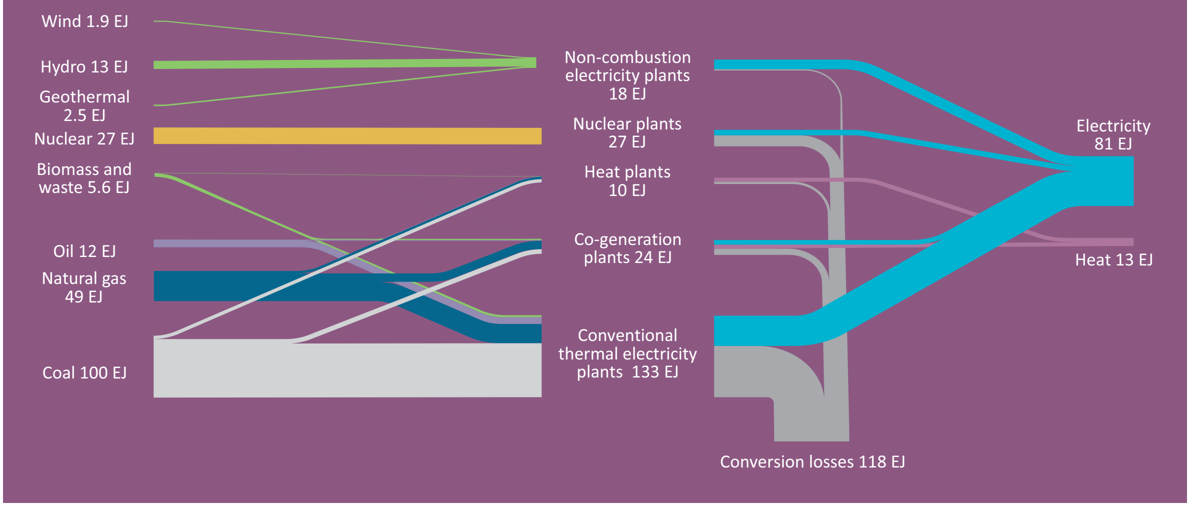
[15] Co-generation is also commonly referred to as combined heat and power (CHP). This report uses the term co-generation to refer to the simultaneous generation of heat and electricity.

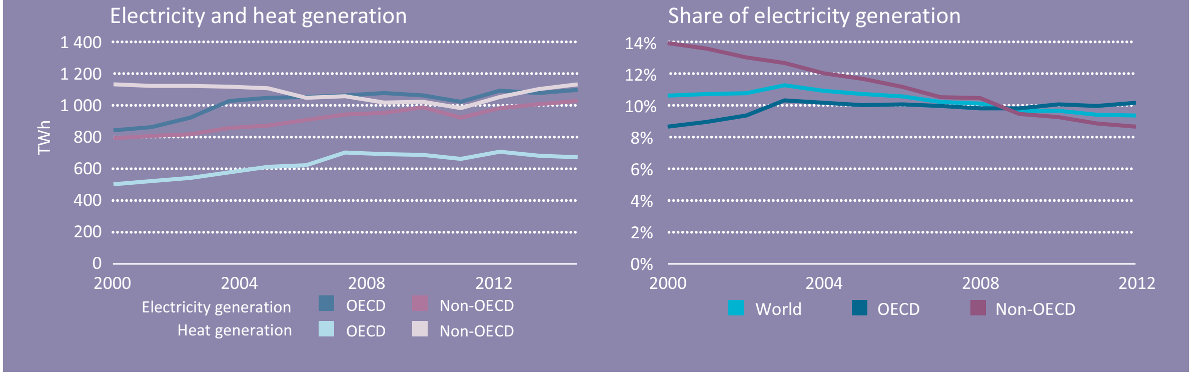
[16] Where deep energy renovation or retrofit is defined as a reduction in energy consumption of at least 50% or to not more than 60 kWh/m^2 for building code loads (e.g. space conditioning, water heating and hardwired lighting), (GBPN, 2013).

[17] 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.

2.46 Energy flows in global power and heat generation in 2012



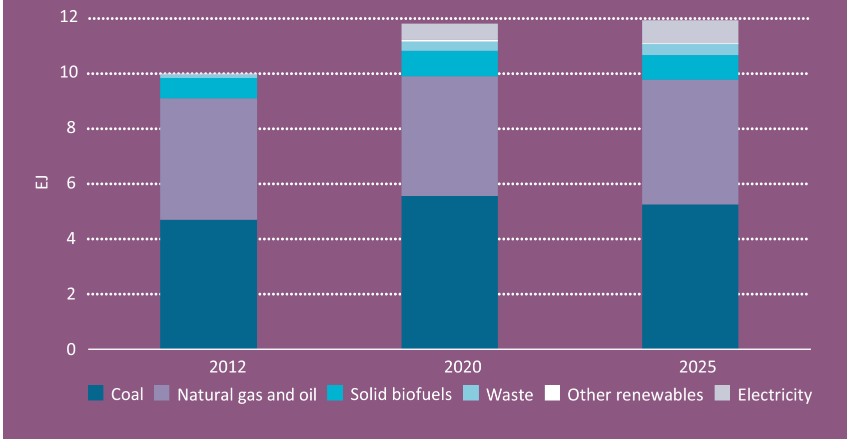
2.47 Co-generation trends



22%

INCREASE IN DISTRICT COOLING CAPACITY FROM 2007 TO 2011 (IN 9 COUNTRIES WHERE DATA WERE AVAILABLE)

2.48 District heating fuel mix



For sources and notes see page 133

Renewable heat

● Improvement needed
~ Limited developments

Modern renewable energy use for heat, excluding the traditional use of biomass, continues to grow, albeit slowly. Growth is driven by support policies in key markets, and to an increasing extent by cost-competitiveness with fossil fuel use for heating. However, only around 50 countries have introduced support measures for renewable heat compared with more than 130 with policies supporting renewable electricity.

Recent trends

Renewable final energy use for heat (RE-FEH) accounted for about one-quarter (46 EJ) of world final energy use for heat (FEH) in 2013, with the largest part (32 EJ) still coming from traditional use of biomass in developing countries.[18] Modern renewable energy technologies, such as modern bioenergy, solar thermal and geothermal, accounted for 14.3 EJ of energy use for heat in 2013, up from 12.4 EJ in 2007, an average rise of 2.4% per year. In the buildings sector, modern RE-FEH increased from 4.5 EJ in 2007 to 5.9 EJ in 2013, and now provides 7% of the sector's total FEH. District heating has gained importance for distribution of renewable heat in a cost-efficient manner, and 6% (0.4 EJ) of modern renewable heat in buildings is now supplied through district heating networks.

Modern RE-FEH in buildings is expected to reach 8.3 EJ in 2020 or 9% of FEH in buildings, with China accounting for two-thirds (1.6 EJ) of this growth. If current trends continue, modern RE-FEH could reach around 11 EJ in 2025, but uncertainty over post-2020 policy frameworks in some regions, including the European Union, is likely to undermine growth. In general, the potential for renewable heat remains largely untapped, as many markets with favourable conditions do not have policies that would help overcome economic and non-economic barriers. Subsidies for fossil fuels are an additional challenge for the competitiveness of renewable heating technologies in several countries.

Developments have been slower in the industry sector, where RE-FEH grew by only 0.6% annually since 2007, reaching 7.7 EJ in 2013, roughly 10% of total FEH. Bioenergy accounts for 99% of the total RE-FEH, as solar thermal and geothermal energy remain concentrated in sectors with lower temperature heat requirements. In the absence of specific policy support, RE-FEH in industry is expected to grow only slightly faster at 1.6% per year from 7.7 EJ in 2013 to 8.7 EJ in 2020, almost entirely from a greater use of bioenergy. The share of modern renewable heat in total industrial energy use for heat is expected to decrease from 10% in 2013 to 9% in 2020, mainly because overall energy demand for heat in industry is likely to grow at more than 2% per year. Even if renewable energy use for heat in industry continues to grow along current trends – which is not guaranteed given the lack of policy support – its potential for use in industry would still remain largely untapped in 2025.

Tracking progress

Significant improvement is needed because modern renewable heat does not have significant deployment, yet it could contribute to meeting the 2DS by reducing fossil fuel usage and emissions associated with heat demand. Limited availability and consistency of data on energy use for heat in general and renewable heat in particular prevent a more detailed analysis of the heat sector. Reporting of data and quality of official statistics should be improved by filling existing data gaps (see IEA, 2014h).

Recommended actions

As many renewable heating technologies are already mature, policies should mainly focus on removing non-economic barriers that prevent the deployment of modern renewable heat.

Renewable heat needs to be delivered to consumers in an efficient way. District heating (and cooling) networks can play an important role in enabling enhanced use of renewable energy for heat in urban areas.

To enhance the use of RE-FEH production in industrial processes, further RD&D is needed that reduces costs of renewable heat technologies, including heat storage, so that they can meet the specific needs of different industries in a cost-efficient way.

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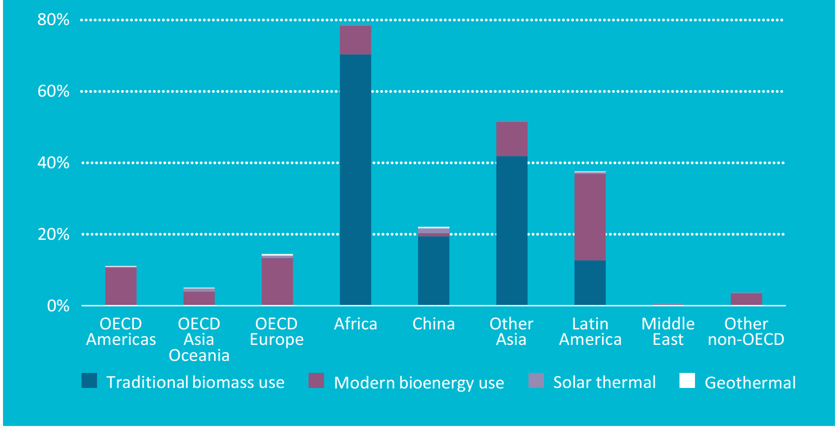
[18] Traditional biomass use refers to the use of fuelwood, animal dung and agricultural residues in simple stoves with very low combustion efficiencies. A decrease in the traditional use of biomass is desired as it is typically associated with indoor pollution and sustainability issues. *See Technology Overview* Notes page 136 for further explanation.

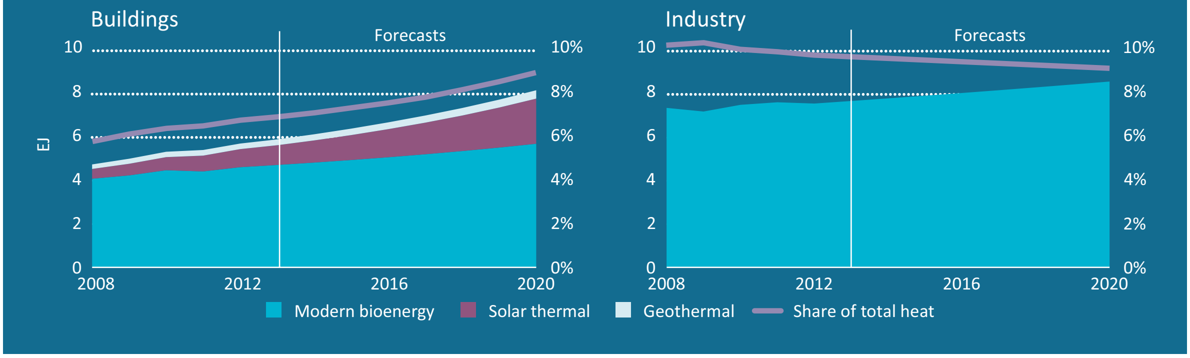
2.49 Share of renewable heat in total FEH



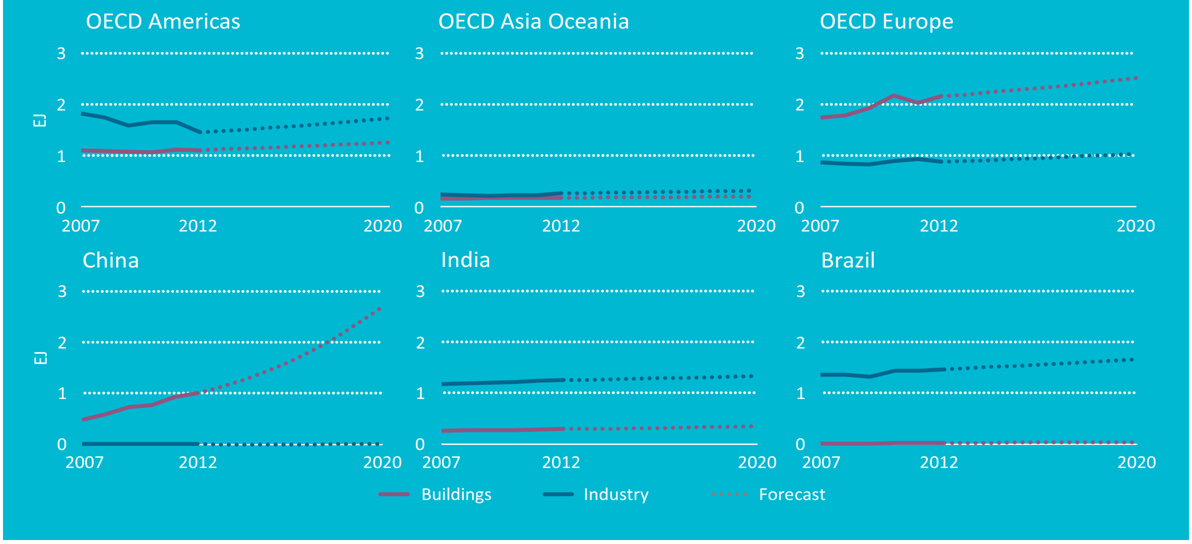
70%

OF GLOBAL RENEWABLE ENERGY USED FOR HEAT IN 2012 CAME FROM TRADITIONAL BIOMASS USE

2.50 Modern renewable energy use for heat by sector



2.51 Modern renewable energy use for heat by region



For sources and notes see page 133

Smart grids

● Improvement needed
~ Limited developments

Smart grids are a key enabling technology for achieving the cleaner energy systems envisaged in the 2DS. Despite false starts and cost overruns deployment of some sub-categories of smart grid technologies has grown quickly in early adopter markets. However, regulatory bottlenecks, and unrealistic expectations are preventing smart grid technologies from reaching the required levels.

Recent trends

As smart grids are involved in system integration, a wide range of factors is driving their development and deployment, not all directly related to clean energy technology. Revenue protection and assurance, as well as reduction of non-technical losses, are driving the adoption of smart meters in many jurisdictions. In many emerging economies, increased efficiency of grid management (including reducing the number and duration of service interruptions) and improved reliability and deferral of investment in reinforcing grid assets are also driving deployment and demonstration. Overall, evidence that some expectations were unrealistic has tempered initial enthusiasm surrounding smart grids – and yet benefits have been realised from advanced metering infrastructure and distribution automation. Distribution automation, in particular encompassing measures to enhance monitoring, control and directionality, is proving to be the fastest-growing technology sub-category. Global investments rose by 23% from 2013 levels, and inventive activity accelerated.

Last year China overtook the United States in annual investment in smart grid technologies. China has one of the world's highest rates of electricity service interruption; growth in smart grid investment reflects the increasing importance of revenue protection and system efficiency and reliability as drivers for these technologies, particularly in emerging economies. Smart meters are perhaps the easiest technology deployment to track: China dominated the meter market in 2013 by installing 62 million meters and now accounts for almost two-thirds of global installations. Deployment of smart grid technologies in the United States slowed significantly from 2013 to 2014 as stimulus funding lapsed, uncertainty persisted over clean energy policy and markets experienced some degree of saturation. In Europe, following rapid deployment in Spain and other initial markets, policy drivers are expected to push smart meter installations from the current 55 million per year to an estimated 180 million in 2020, led by France, Germany and the United Kingdom.

Beyond the deployment of advanced physical network infrastructure, investments in ICT solutions are expected to increase dramatically over the next five years. As changes in market arrangements allow demand response to benefit from wholesale and capacity market payments, ICT solutions showing the benefits of aggregating consumers at the distribution level are being piloted in Japan, Korea and the United States, with an aggregate consumer base of 6.5 million.

Tracking progress

Globally, annual smart grid investments reached USD 14.9 billion in 2013, 5% more than in 2012. The positive trends in distribution automation reflect the future "system of systems" vision for electricity networks envisaged in ETP 2014. As the replacement cycle of the first wave of smart meters begins, investment is expected to accelerate again. Data availability precludes a more complete picture of smart grid deployment.

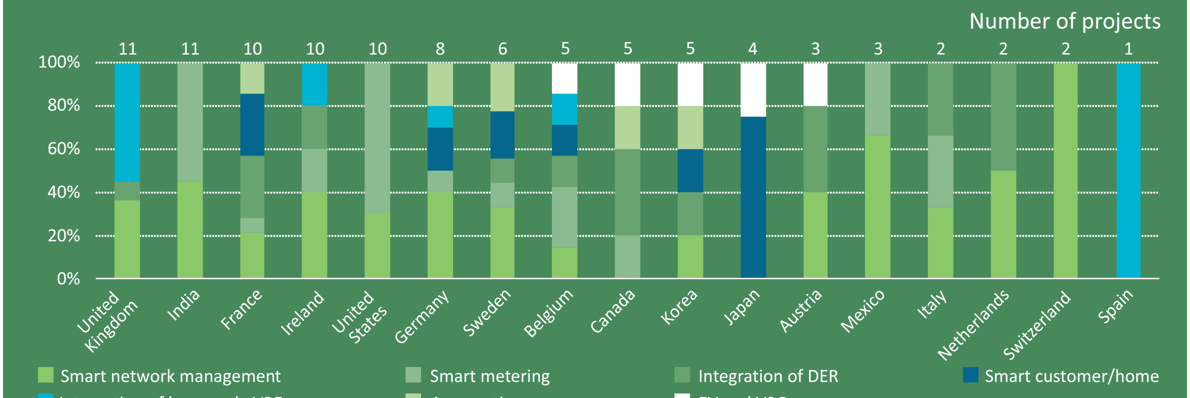
Recommended actions

Smart grid deployment strategies need to be centred on customers and business models. This calls for demonstrating and developing national strategies that articulate the benefits of smart grids to stakeholders.

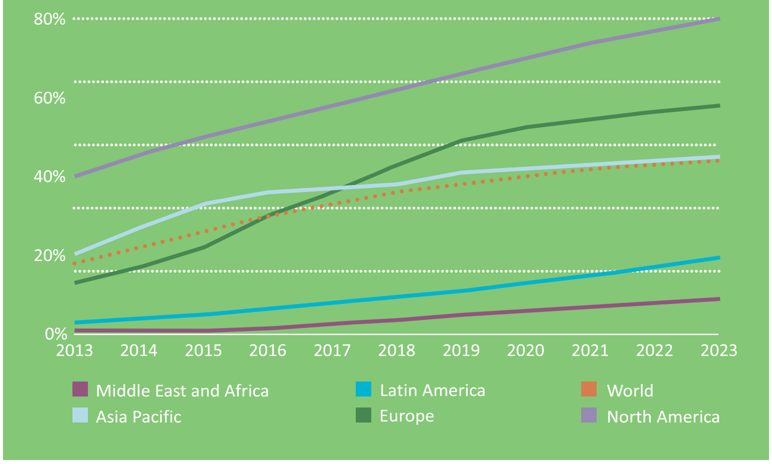
For system operators and utilities, key concerns are technology obsolescence, interoperable technology and system security. Consequently, transparent regulation that allows cost-reflective investment in advanced distribution network technologies will be required for sustained market development.

As electricity markets increase harmonisation of operation in several regions, international standards for underlying infrastructure need to be developed in parallel, in particular to accelerate RDD&D. Methodologies for quantifying the benefits of smart grids (e.g. reductions in duration or frequency of service interruptions) also need to be standardised.

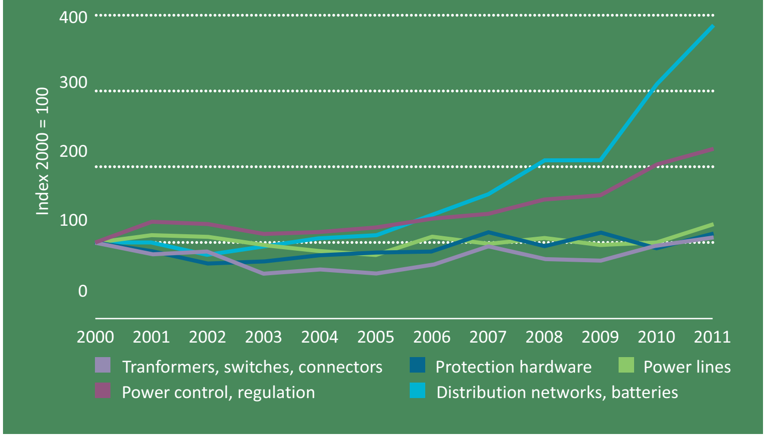
2.52 Sample projects by technology area



2.53 Smart meter penetration in key regions



2.54 Grid technology inventive activity



Deployment drivers

Emerging economies

1. Reliability
2. System efficiency
3. Revenue collection and assurance
4. Renewable power
5. Economic advantages
6. Generation adequacy

Developed economies

1. System efficiency
2. Renewable power
3. New products, services and markets
4. Customer choice and participation
5. Reliability improvements
6. Asset utilisation

For sources and notes see page 133

Energy storage

● Improvement needed
↗ Positive developments

Storage is expected to contribute to meeting 2DS targets by providing flexibility to the electricity system and reducing wasted thermal energy. The current outlook for energy storage is promising, but the high capital costs of storage technologies remain a barrier to wide deployment.

Recent trends

Large-scale energy storage capacity was over 145 GW in 2014, of which over 97% was accounted for by pumped hydro storage. While this total includes 2.4 GW of grid-connected thermal energy storage, the actual value is likely to be significantly higher, as thermal energy storage technologies not connected to networks are particularly difficult to capture in global statistics.

Rapid deployment of wind and solar PV energy in several countries has led to integration challenges and the need for more flexible resources, including storage. Between 2005 and 2014 there was a sharp increase in the deployment of large-scale batteries (from 120 MW to 690 MW) and thermal energy storage (from 250 MW to 2 420 MW).

Costs for large-scale batteries have shown impressive reductions, thanks in part to ambitious EV deployment programmes and greater demand for frequency regulation, spurred in some cases by variable renewables deployment. Large-scale batteries are particularly well suited to respond to additional demand for ancillary services. The cost of a lithium-ion battery for grid-scale storage for frequency regulation has shown the largest decline, falling more than three-quarters since 2008 to reach about USD 600/kWh in 2013 (Fernands, S., 2014). This cost reduction was accompanied by a 250% increase in the cycle life times of these batteries, from 2 000 cycles in 2008 to 5 000 in 2013.

As deployment of variable renewables continues to rise, the demand for energy storage technologies is also expected to grow. A wide range of forecasts exists for the deployment of large-scale battery energy storage over the next decade, from just over 11 GW (BNEF, 2014a) in 2020 to 40 GW (IHS, 2014) in 2022, while the potential manufacturing capacity that could be delivered is as high as 130 GW (AES Storage, 2014) in 2024.

Many governments have been supporting energy storage technologies through policies including funding for demonstration projects, subsidies for small-scale storage with PV and mandatory storage requirements for utilities. One such requirement introduced in California requires investor-owned utilities to procure 1 325 MW of energy storage by 2022. Recent action in the United States (FERC Orders 755 and 784) reveals how a market-based approach can accelerate deployment by allowing companies other than large utilities to sell ancillary services in the electricity market and by requiring operators to compensate for frequency regulation.

Tracking progress

Energy storage can contribute to meeting the 2DS, but high costs remain an obstacle to wider deployment, so improvement is needed. More work should be undertaken to improve the quality of statistics and fill existing data gaps.

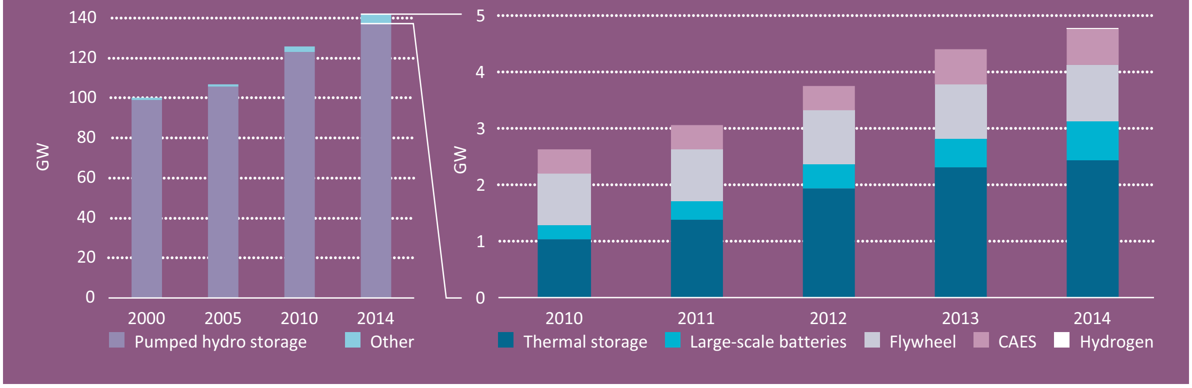
Recommended actions

Investments are required in R&D for early-stage energy storage technologies. Technology breakthroughs are needed in high-temperature thermal storage systems and scalable battery technologies, as well as in storage systems that optimise the performance of energy systems and facilitate the integration of renewable energy resources.

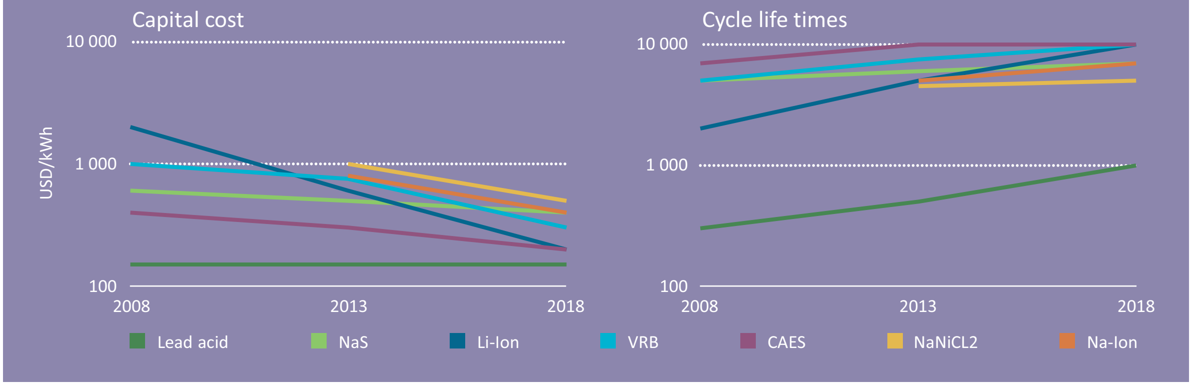
It is vital to develop marketplaces and regulatory environments that accelerate deployment of energy storage technologies. Price distortions need to be eliminated and benefits staking enabled to allow energy storage systems to be compensated for providing multiple services over their lifetime.

Policy makers need to support assessments of the value of energy storage in specific regions and energy markets. They should also promote the development and adoption of tools devoted to evaluating energy storage project proposals.

2.55 Installed capacity for grid connected storage



2.56 Grid-scale battery storage for frequency regulation



2.57 Thermal energy storage capacity

807

GW OF SOLAR THERMAL ENERGY INSTALLED GLOBALLY (566 IN CHINA, 155 IN THE EUROPEAN UNION)

31 780

ICE OR WATER STORAGE PLANTS IN JAPAN WITH A TOTAL CAPACITY OF 1.91 GW

THREE PIT-HEAT WATER STORAGES OF

13

GW INSTALLED IN DENMARK

550

UNDERGROUND THERMAL ENERGY STORAGE UNITS INSTALLED IN SWEDEN WITH A CAPACITY OF 290 MW. 100 UNITS IN BELGIUM WITH A CAPACITY OF 13.6 MW AND A 0.6 MW PLANT IN DENMARK

For sources and notes see page 133

Hydrogen and fuel cells

● Improvement needed

~ Limited developments

Hydrogen is a flexible energy carrier with potential applications across all end-use sectors. It is one of only a few potential near-zero-emission energy carriers, along with electricity and biofuels. Hydrogen is most suitable for the storage of large quantities of energy over a long time, such as low-carbon electricity, or small quantities under restricted space and weight requirements, which makes it a promising fuel for low-carbon transport.

Recent trends

Around 8 GW of electrolysis capacity is installed worldwide, accounting for around 4% of global hydrogen production (Decourt et al., 2014). Alkaline electrolysers are the most mature technology and are already commercially available, while proton exchange membrane (PEM) and solid oxide electrolysers have higher potential for cost reductions and efficiency improvements. Electrolysers are highly modular systems, which makes the technology very flexible in terms of output capacity but also limits the effects of economies of scale, as even big electrolysers are based on identically sized cells and stacks.

According to the US DOE *2013 Fuel Cell Technologies Market Report* (US DOE, 2014a), between 2008 and 2013 the global market of fuel cells (FCs) grew by almost 400% (shipped units), with more than 170 MW of FC capacity added in 2013. Currently, more than 80% of FCs are used in stationary applications, such as FC micro co-generation, back-up and remote power systems. While the United States ranks first in terms of added FC power capacity, Japan ranks first in terms of delivered systems, due to the successful upscaling of the Japanese EneFarm micro FC co-generation system.

Globally, around 600 FCEVs are running in demonstration projects. Since driving performance of FCEVs is comparable to conventional cars and refuelling time is about the same, FCEVs can provide the mobility of conventional cars at potentially much lower carbon emissions. Some manufacturers have announced pre-commercial market introduction of FCEVs at prices of USD 60 000 to USD 100 000. Costs of the FC system are the main reason for high vehicle prices. According to the US DOE, costs of PEM FC systems for mobile applications could be significantly reduced if large-scale production processes were initiated and theoretic production costs materialised. Announced plans for FCEV market introduction range from a few thousand vehicles in the near future up to several hundred thousand by 2025.

Overcoming the "chicken and egg" problem is the biggest barrier for larger deployment: FCEVs require hydrogen stations. Currently, around 80 stations are in operation worldwide. Ambitious plans envisage the installation of around 800 hydrogen stations worldwide by 2020, clustered around early development centres and along main connecting corridors to refuel the first commercial generation of FCEVs.

Tracking progress

Although many hydrogen and FC technologies are still in the demonstration phase, some are close to early adoption, such as FCEVs and PEM electrolysers. FCEVs now have to demonstrate their economic viability as deployment grows beyond several hundred vehicles in demonstration projects and niche market applications such as materials handling.[19] Similarly, the use of PEM electrolysers at capacities of several megawatts, to generate hydrogen from otherwise curtailed low-carbon electricity, needs to be brought forward to finally prove the economic feasibility of large-scale and long-term energy storage systems and power-to-gas systems.

Recommended actions

To foster the uptake of hydrogen as an energy carrier, it is imperative to sustain RD&D, for transportation and stationary applications as well as for hydrogen storage, production and delivery. To accelerate deployment, codes and standards need to be developed and harmonised; policies and incentives such as fuel economy regulations and tax credits for low-carbon vehicles need to be strengthened; and refuelling and recharging infrastructure needs to be put in place. Further support is needed for research that quantifies benefits and challenges of energy system integration, to enable better understanding of the application of hydrogen technologies in a broader energy system context.

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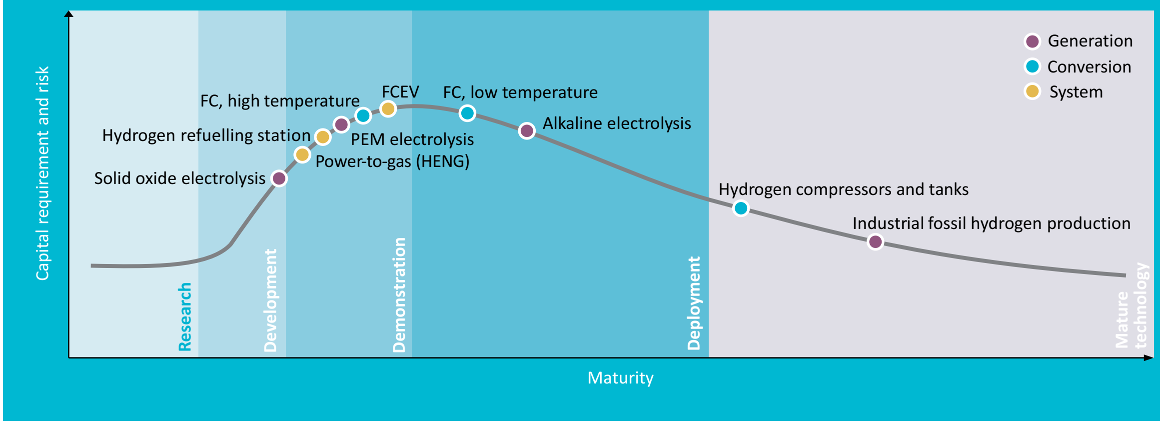
[19] The largest part of FC units shipped in the transportation sector is currently composed of FC forklifts.

2.58 Maturity of hydrogen technologies and systems



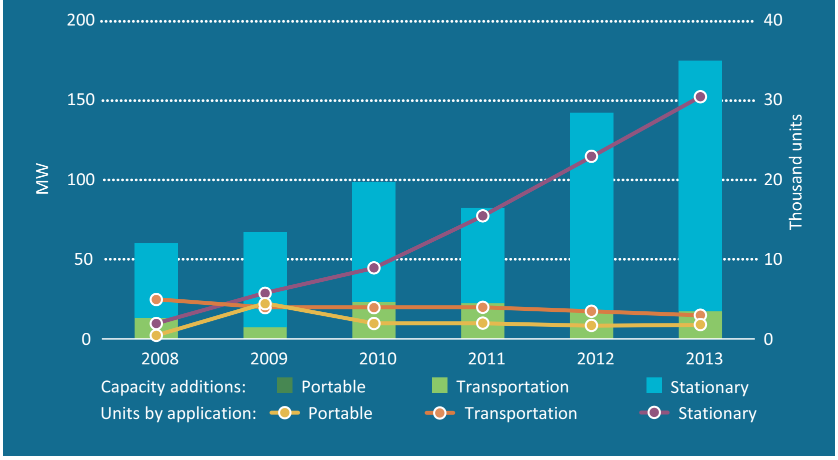
85

EXISTING HYDROGEN STATIONS IN EUROPE, JAPAN, KOREA AND CALIFORNIA

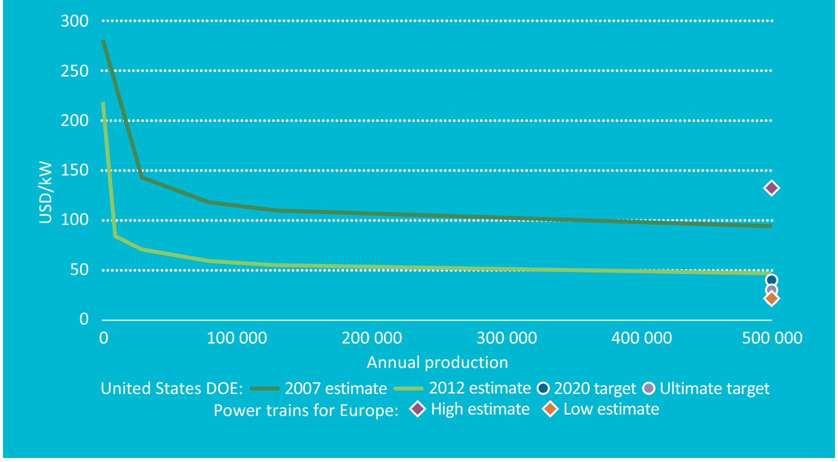
800

PLANNED TO 2020, ALMOST TEN TIMES THE EXISTING NUMBER OF STATIONS

2.59 Market development for fuel cells



2.60 Production costs for PEMFCs for transport



For sources and notes see page 133

Metrics for energy sector decarbonisation

National commitments on climate change are likely to include actions in the energy sector with both near-term and longer-term impact. A diverse set of energy metrics will be required to identify potential and track progress against a range of nationally determined mitigation goals.

Key findings

- Energy metrics can be used to identify potentials and set ambitious yet realistic national targets for emissions reduction. They can be used to inform the development of Intended Nationally Determined Contributions (INDCs), as well as to monitor progress on climate change action.
- Decarbonisation of the electricity sector will need to accelerate over the next decade to reach 2DS targets. By 2020 the average lifetime emissions intensity of all new-build plants in China, India and the United States will need to fall to levels near half that of current gas-fired plants or about one-third of the current global emissions intensity of power generation. In the European Union, the average new-build plant is nearly decarbonised by 2020.
- Technology-specific indicators to track progress on development and deployment should be complemented by sector-specific metrics in the power, buildings, industry and transport sectors. These metrics will cover both energy supply and energy demand indicators.
- IEA work in energy statistics and indicators, technology tracking, and energy sector modelling can contribute to the development of metrics and tracking frameworks for energy sector decarbonisation, either inside or outside the UNFCCC process.

Opportunities for policy action

- Sector- and technology-specific energy sector metrics should be identified at the country level, to underpin the development and tracking of ambitious and achievable national energy sector decarbonisation strategies.
- Concerted efforts should be made to scale up data collection and development of metrics in countries where lack of data poses a significant barrier to setting targets, meeting targets, and measuring progress in energy sector transformation.
- Governments should support the collection of detailed end-use energy data and the development of energy efficiency indicators that can be used to identify energy efficiency potential, monitor trends in energy use and monitor progress on policies.
- Energy metrics should be used in the UNFCCC process to track energy-framed INDCs (such as renewable energy targets), and also to track the underlying drivers of long-term decarbonisation.

The previous sections of this publication track progress of key technologies for energy sector decarbonisation at the global level. This section shifts the focus to individual countries, and discusses different types of metrics that could be useful to track progress on national actions towards energy sector decarbonisation. It illustrates how a series of energy sector-specific indicators could be used to set national targets and track progress.

Setting and tracking decarbonisation goals is of key importance in the international climate change negotiations process. A new climate agreement will be negotiated under the UNFCCC by the end of 2015 and come into effect from 2020. Parties to the UNFCCC will communicate their intended mitigation goals and actions for this new climate agreement during 2015. These INDCs will cover a diverse range of measures, including targets for GHG levels in the 2020-30 time frame and long-term GHG targets for 2050 or beyond. As the energy sector produces two-thirds of global GHGs, countries could also commit to specific goals and actions aimed at decarbonising the energy sector.

The choice of metrics used to set goals and track progress matters a great deal. First, understanding and accurately tracking all countries' actions, whether in terms of GHGs or specific energy metrics, will be critical to building the mutual trust that a successful international climate regime will rely on, as well as understanding the aggregate impact of all countries' efforts. Second, the choice of metrics used to express climate goals can itself have an influence on what decarbonisation actions countries choose to take, and the ambition of these efforts.

Choosing the right metrics for energy sector decarbonisation

In preliminary discussions on the 2015 climate agreement, it is becoming clear that a range of nationally determined mitigation goals, tracked via a variety of metrics, could be included in addition to short- and long-term GHG targets. Tracking a wider range of metrics would also help countries to better understand opportunities for action and associated benefits, and thus drive energy sector transformation in a more targeted manner in the short term. For countries with GHG goals for 2050 or beyond, a basket of energy sector metrics will be needed to understand whether energy infrastructure shifts and development of key technologies are on track. There are therefore many reasons that countries may be motivated to use energy sector goals and metrics, alongside and to support GHG emissions reduction goals (Prag, Kimmel and Hood, 2013):

- **Energy sector metrics can link more directly to policy influences.** Short-term total annual GHG emissions can vary for many reasons, including changing economic conditions, fuel prices and weather. Targets that are more closely linked to policies under the control of government (for example, a mandated share of renewable electricity generation) may be easier to adopt, as outcomes are more easily influenced or directed by policy, and decision makers can have more confidence that targets can be delivered.
- **The primary purpose of energy sector policies is often not emissions reduction.** Clean energy policies are implemented for a wide range of reasons and often have multiple benefits, of which emissions reduction is only one. For example, energy efficiency interventions can have benefits for energy security, health and well-being, industrial productivity and competitiveness, energy providers, energy consumers, public budgets, and macroeconomic outcomes, including jobs (IEA, 2014a). A focus on GHG outcomes that ignores wider benefits could result in less ambitious action.

- **Different metrics can reframe the challenge positively.** In the UNFCCC negotiations, emissions reduction has historically often been framed as a burden to be shared among countries. This sends the message that while action on climate change is necessary, it will be an economic burden. Discussions on the 2015 agreement are instead seeking to frame climate action positively, as an opportunity to be seized. Use of alternative metrics that express positive attributes (for example, improving GDP per unit of energy input, or increasing clean energy production) can help change the communication and perceptions of climate goals.

- **Alternative metrics can highlight short-term actions that underpin long-term transformation.** To date, most GHG reduction goals have short-term (five- to ten-year) targets.[20] This encourages implementation of the least-cost measures for short-term emissions reduction, which are not necessarily the same actions that would be cost-optimal from the perspective of long-term transformation. Tracking actions underpinning long-term transformation, such as lock-in of infrastructure and development of key technologies, would complement short-term GHG goals.

There is a wide range of metrics that could be used to track countries' energy sector climate goals (IEA, 2014b). In general, these will include metrics of the following types:

- **Metrics expressed in GHG terms,** such as total annual GHG emissions or emissions per unit of GDP or production, whether economy-wide, for the energy sector or disaggregated by sub-sector. These metrics capture the aggregate climate outcome of all energy sector actions. Under the UNFCCC, countries report national GHG inventories as part of the biennial reporting process.

- **Metrics expressed in non-GHG terms,** but which are nonetheless likely to have an impact on short- to medium-term GHG emissions levels. This category would include many energy sector metrics such as those used to track energy efficiency, renewable energy and other low-carbon energy deployment goals. Using such metrics can result in goals linked more closely to national priorities and available policy levers. Some high-level metrics of this type can be derived from GHG inventory data, but many will need additional data collection, and national capacity to collect and analyse specialised data.

- **Metrics that track actions with a significant impact on long-term emissions,** but minimal impact on short- to medium-term emissions (i.e. pre-2030). These would include tracking R&D of key technologies such as CCS, advanced vehicles, or infrastructure investment trends that lead to either decarbonisation or the lock-in of high-emissions infrastructure. Choosing metrics that capture progress towards long-term decarbonisation goals relies on capacity to collect and analyse relevant data, and on modelling capacity to understand countries' potential decarbonisation pathways.

A distinction can also be drawn between metrics that track the outcomes of policy (e.g. energy consumption per GDP), and metrics that track the drivers of emissions reduction (e.g. retrofit rate of existing buildings). These play complementary roles: *outcome* metrics are important to understand overall progress after implementation, while *driver* metrics give a more direct understanding of the transition pathway required and the consistency of current actions with the desired goals.

Summing up the parts: Energy sector decarbonisation metrics

To enable a more holistic or integrated view of trends in the energy sector, high-level indicators such as the IEA Energy Sector Carbon Intensity Index (ESCII) and the commonly used energy intensity indicator (total energy use per GDP) offer a starting point and can

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[20] Long-term carbon budgets, for example those in UK legislation, are the exception rather than the rule.

be developed at the global and country levels.[21] More detailed metrics at the sector level should also be developed to identify energy efficiency and emissions reduction potentials, and to enable comparisons among countries so that effective policies and measures can be identified. The sum of these individual metrics can help to better identify potential pathways for decarbonising the energy sector and aid countries in setting ambitious yet realistic energy and climate targets in line with their national circumstances.

The most appropriate set of metrics (or indicators) to evaluate and monitor progress in the energy sector towards nationally determined mitigation goals will vary from country to country, depending on local conditions, energy use trends, data availability and national targets. In addition to the ESCII and emissions intensity for the energy sector as a whole, these metrics should cover at least the four main sectors of power, buildings, industry and transport. The set should include measures of energy supply and demand, and both outcome and driver metrics. While some metrics are more comprehensive and refined than others, it is important to underline that no single metric can fully portray a country's progress towards a decarbonised and efficient energy system; an integrated assessment incorporating the most relevant indicators should be used. Where data are available, countries should strive to track progress using sub-sector, energy end use or equipment or technology indicators. In other cases, countries could use sectoral indicators until sufficient data are available to develop higher-level indicators.

Role of electricity decarbonisation: A supply-side example

Electricity generation accounts for 25% of all global GHG emissions and almost 40% of all energy-related CO_2 emissions, as well as 38% of total primary energy (IEA, 2014c), so it is vital that the sector move from carbon-intensive fossil fuel-fired power to low-carbon options.

To evaluate progress and trends in the power sector comprehensively, technology-specific metrics for tracking progress on renewables, nuclear, efficient fossil fuel-fired power plants and CCS should be combined with sector-specific metrics such as average emissions per kilowatt hour produced and share of zero- or low-carbon electricity (Figure 2.61). These two metrics provide an overall picture of trends in the CO_2 intensity of electricity generation and can be categorised as overall energy supply sector (level 1) metrics. Additional indicators such as capacity deployment and generation of low-carbon generation or shares of specific renewables, nuclear or CCS deployment can be categorised as sub-sector (level 2) metrics and can help countries to identify the mix of technologies needed to avoid lock-in of carbon-intensive power generation. Where possible, technology-rich power sector modelling and scenario development (such as the IEA 2DS and techno-economic TIMES model) should be used to identify potential pathways for decarbonising the electricity sector and end-use sectors. Such tools require detailed resource assessments and electricity demand profiles that may not yet be available in all countries, so the first step may be to develop such assessments and profiles. Indicators at the more disaggregated technology or equipment level (level 3), covering electricity transmission and distribution or new-build plants emissions intensity, could also be developed.

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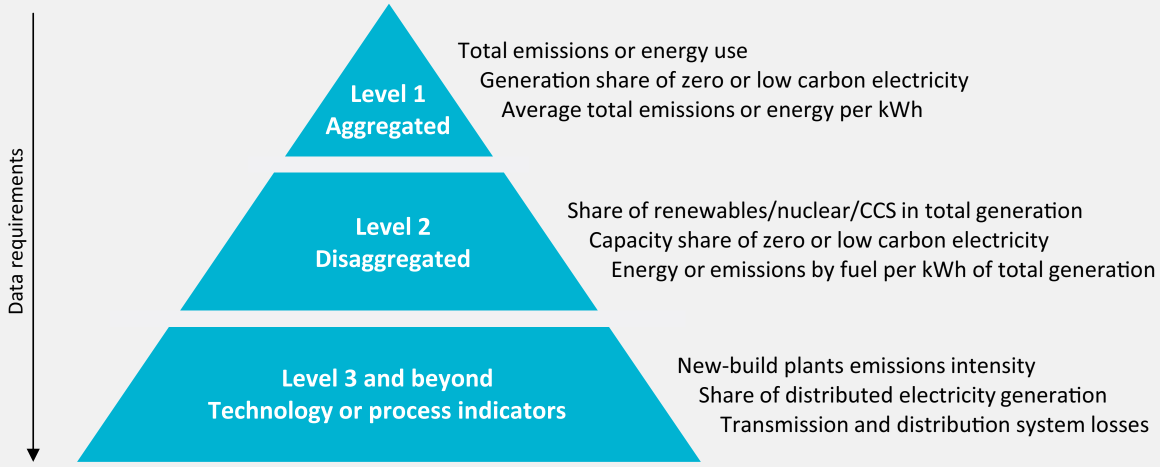
[21] Total carbon intensity of the energy mix (ESCII) and energy intensity, as well as GDP per capita and population constitute the four high-level Kaya identity factors.

Figure 2.61 Power sector decarbonisation metrics



Notes: These metrics are intended for illustrative purposes and not to be a definitive list. Levels do not indicate importance of a given metric. Figures and data that appear in this report can be downloaded from www.iea.org/etp2015.

Key point *A conceptual structure of an indicators pyramid portrays a hierarchy of energy indicators from most aggregated (top) to detailed indicators with significant data requirements.*

The combination of low-carbon power generation technologies each country needs will depend on the country's current generation mix, available national resources, the maturity of its generation assets, the state of its electricity grid, expectations of electricity demand growth, electricity demand profile, resource endowment, energy prices and public acceptance of various low-carbon technologies. Countries should take these factors into consideration when setting targets and monitoring progress.

Metrics to help avoid power sector lock-in

Metrics can translate long-term goals into short-term actions consistent with that goal. To avoid locking in high-emissions infrastructure, it is vital to articulate what kind of short-term investments are consistent with long-term pathways that limit warming to 2°C, and to track progress in these investment patterns. For example, the average emissions intensity of new investments in power generation could be tracked and compared with the global fleet average emissions intensity to track what is consistent with a 2°C pathway (Figure 2.62).

To achieve the sharp decline in the average fleet-wide emissions intensity[22] of power generation needed to meet the 2DS, the average global emissions intensity of new generation[23] must be lower than that of natural gas or about one-third of current global levels in the period to 2020, and only 10% of today's levels after 2020 (Figure 2.62). Achieving this global 2DS target will require deeper reductions in emissions intensity in some regions than others; further details on these pathways are elaborated below for China, the European Union, India and the United States.

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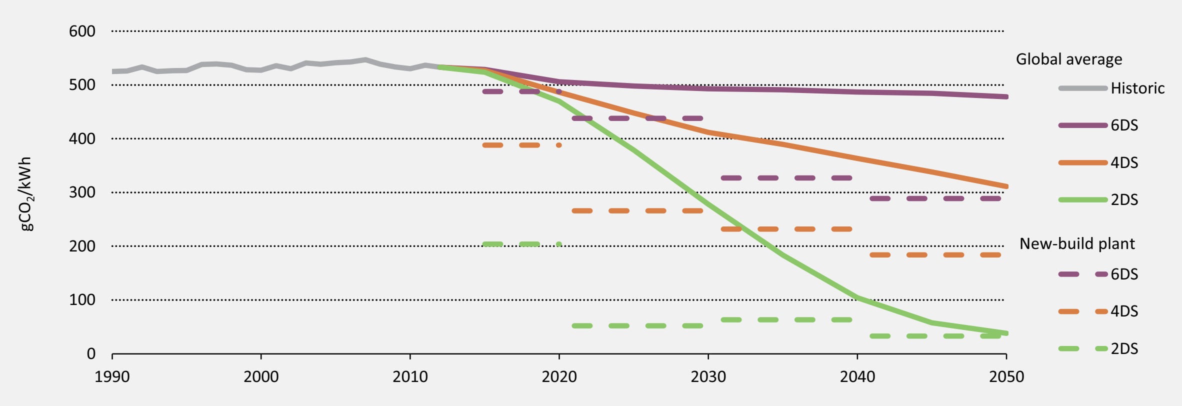
[22] Fleet-wide average emissions refer to CO_2 intensity across all operating plants, irrespective of their age.

[23] The lifetime emissions intensity of a new investment is calculated by dividing the modelled emissions generated by these plants by their total generation in each scenario over the lifetime of the plant over the model horizon up to 2050. High-efficiency coal plants will be later retrofitted for CCS and hence lead to relatively low lifetime emissions intensity.

Figure 2.62 Global fleet average and new-build plants emissions intensity of power generation in IEA scenarios



Key point *To achieve the sharp decline in fleet-wide emissions intensity in the 2DS, the average emissions intensity of new generation must be lower than that of natural gas by 2020 and only 10% of today's levels after 2020.*

A metric that tracks the expected lifetime emissions intensity of new investment in power generation would therefore be a useful addition to current measures of fleet-average parameters. Expected lifetime emissions from new plants could be reported based on emissions intensities, expected running hours and expected plant lifetime. Including plans to retrofit for CCS in these estimates would also focus greater attention on the need for timely development of CCS technologies.

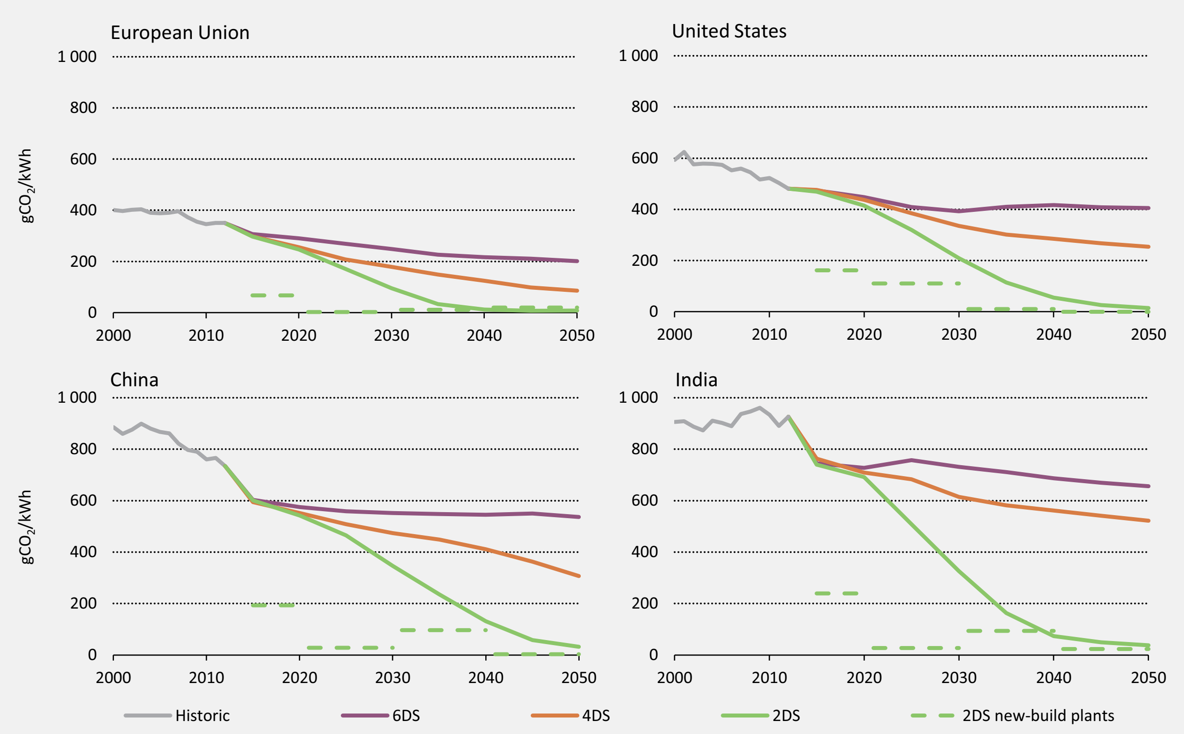
New-build plants emissions intensity could also be tracked by considering investment spending, rather than capacity or generation. In the 2DS, from 2020 to 2030 around 85% of global investment in new generating capacity needs to be in non-fossil fuel or CCS-equipped plants (IEA, 2014f).

The analysis above can be applied at the national/regional level to help inform investment decisions and better understand their long-term impact on emissions. Using the 2DS, electricity sector metrics at the national/regional level have been identified for China, the European Union, India and the United States (Figure 2.63). These four economies account for approximately 60% of total electricity production, which is expected to rise to 85% by 2050, so it is crucial for them to take early action to reduce global energy-related emissions.

The average CO_2 intensity of electricity generation has fallen since 2000 in all of these economies except India. China and the United States have reported the largest drops. Policies to phase out inefficient coal plants and wider deployment of wind and solar power helped to cut emissions intensity by 17% in China between 2000 and 2012. The development of cheap shale gas in the United States triggered a switch from coal to gas-fired generation that lowered average emissions intensity by 19%.

In the European Union, reductions in emissions intensity have been more modest as policies to phase out nuclear power, combined with ongoing use of coal, have partially offset rapid expansion of renewable generation. Since 2000, the emissions intensity of electricity generation in India has risen slightly (by 2%) because rapid growth in electricity demand has been mainly satisfied by subcritical coal plants and because existing coal capacity is ageing and poorly maintained.

Figure 2.63 Power sector fleet average and new-build plants emissions intensity



Key point *Emissions intensities of new-build plants should be lower than natural gas-fired power generation (350 gCO_2/kWh) by 2020 and reaching near decarbonisation levels by 2030.*

In all regions and in all scenarios, the average emissions intensity of power generation is expected to decline as more low-carbon electricity sources are deployed. Only the 2DS, however, describes a more dramatic transformation, in which in all four regions by 2020 the average emissions intensity of new-build plants needs to be well below that of gas-fired power generation (350 gCO_2/kWh) and reaching near decarbonisation levels by 2030 (less than 30 gCO_2/kWh in all regions but the United States). To achieve the sharp decline in the average intensity of power generation in the 2DS, a significant share of unabated coal-fired power will need to be retired or retrofitted with CCS, in addition to the deployment of low-carbon generation.

In China and India, where electricity production is dominated by coal-fired plants, demand for electricity continues to rise with economic development and increased living standards. In the 2DS, these countries still deploy significant shares of fossil-fueled plants over the next decade, but mainly highly efficient coal plants that later will be retrofitted with CCS; together with low-carbon power generation such as renewables and nuclear, this helps to reduce the average intensity of new-build plants. After 2030, electricity demand growth will level off in China and the costs of low-carbon generation technologies will be more competitive. The average intensity of new-build plants in China and India will need to converge to near decarbonisation, reaching levels similar to those in the European Union. In 2040, the emissions intensity of new-build plants increases in China and India because of the need to replace older fossil plants used for peaking and to meet flexibility requirements from high shares of variable renewables.

While decarbonising electricity may be considered the most important supply-side measure, it is not the only one. Options to replace the use of fossil fuels in the end-use sectors are also important and are highlighted in later sections, as are measures in the oil, gas and coal industry to improve efficiency and reduce emissions.

Benefits and role of early action on energy efficiency

While decarbonising the energy supply will be central to achieving ambitious emissions reduction targets, countries will also need to take action to reduce or limit growth in energy demand. The importance of energy efficiency in reducing emissions is undisputed, yet progress on implementing energy efficiency measures continues to remain off track. In some countries this is due to insufficient understanding of where energy is used and where the largest potential exists for reducing energy consumption. All countries need to understand their consumption by end use and to be able to track these changes over time. The development of energy efficiency indicators at sector, sub-sector, energy end use or technology level (levels 2, 3 and beyond) that track trends in energy use can help countries to identify energy savings potentials and priorities, as well as developing more effective energy efficiency policies.

Where detailed energy end-use data is available (e.g. for water heating or for production of ammonia), countries should aim to track energy efficiency at the sub-sector, end use or technology level (levels 2, 3 and beyond in Figures 2.64, 2.65 and 2.66). In countries where limited data are available, sectoral level indicators (e.g. energy use in the residential sector per capita) can be used as a proxy to monitor energy efficiency trends until data collection systems allow more comprehensive evaluation (level 1 in Figures 2.64, 2.65 and 2.66). The two IEA energy efficiency indicator manuals describe in detail how to develop and use such indicators (IEA, 2014d; 2014e).[24]

Energy efficiency indicators are considered *outcome* metrics and should be combined with *driver* metrics that can determine long-term emissions trajectories. In the buildings sector, driver metrics include rates of implementation for deep renovation or stringent building codes for new buildings. In the transport sector, driver metrics include vehicle fuel economy standards or deployment of advanced vehicles such as EVs or FCEVs. The following section highlights possible metrics for the three largest energy demand sectors: buildings, industry and transport. Relevant countries could also develop metrics for energy use in agriculture and other transformation sectors (e.g. refineries).

Sustainable buildings: Residential and services energy use and emissions

Metrics to monitor trends in energy use and emissions in the buildings sector should include energy efficiency indicators for the residential and services sector as well as overall buildings energy and emissions intensity. Such measures need to cover both energy demand and energy supply. For countries where limited data are available, sectoral indicators such as building energy consumption per capita or share of renewables in buildings provide a starting point (level 1 in Figure 2.64). Where the necessary end-use data are available for residential and services, more detailed indicators can be developed for each sub-sector or end use (level 2) or equipment type (level 3 or beyond, e.g. technology or equipment by fuel type in Figure 2.64).

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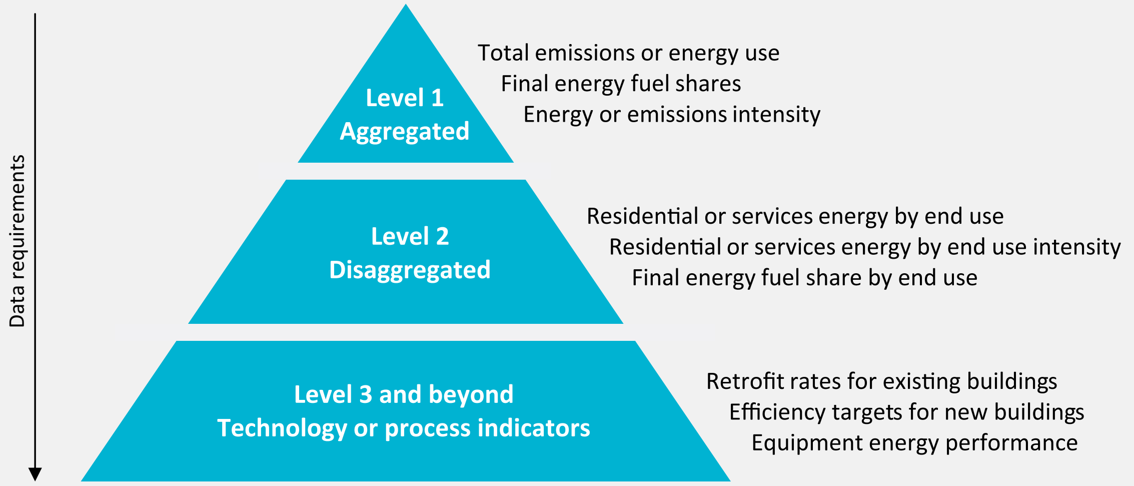
[24] www.iea.org/topics/energyefficiency/subtopics/energyefficiencyindicators/.

The most important end uses for which indicators should be developed will depend on the current and expected profile of energy use in the buildings sector in each country. In cold climates, for example, space heating often accounts for more than half of all energy use. In warm climates, appliances often use the largest share of energy; with potentially high growth in energy use for space cooling, particularly in lower-income countries where air conditioning has yet to be widely deployed. Actions that have the largest impact on a country's buildings energy use should be prioritised.

Figure 2.64 Metrics to track progress in buildings



Note: This figure is intended for illustrative purposes, not as a definitive list of indicators.

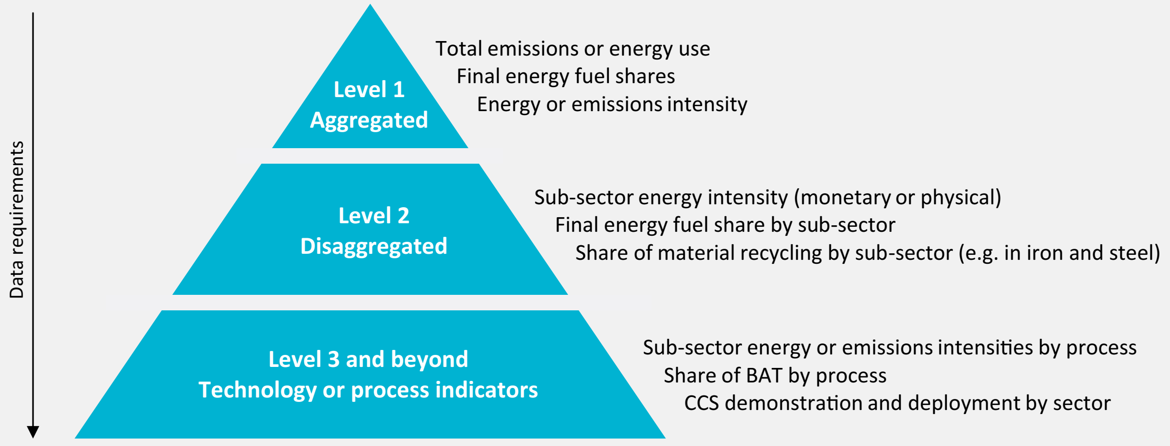
Key point *Aggregate indicators provide a general explanation of trends in energy consumption, but to understand the key drivers and to provide policy-relevant analysis on how to influence these trends, detailed disaggregated indicators are required.*

Industrial transition: Industry energy use and emissions

Significant progress has been made in reducing energy use and emissions in industry, particularly in the most energy-intensive sectors (steel, cement, chemicals, paper and aluminium), driven by efforts to reduce the high share of overall costs associated with energy. Countries have also recognised the need to prioritise action in these industries; many have already implemented policies aimed at reducing both energy use and emissions. Industry will need to focus on using more low-carbon fuels and feedstocks, as well as developing new technologies to reduce energy and emissions even further.

Metrics to monitor trends in industry should cover energy efficiency indicators and energy supply, as well as RD&D metrics for the development and deployment of new process technologies (e.g. smelt reduction technologies in steel) and other measures (Figure 2.65). Driver metrics such as those related to the development of carbon capture technologies for industry will be particularly important in the long term, given the need to reduce process-related emissions from sectors such as cement and steel, especially in those countries where consumption and production of these materials is growing rapidly.

Figure 2.65 Metrics to track progress in industry



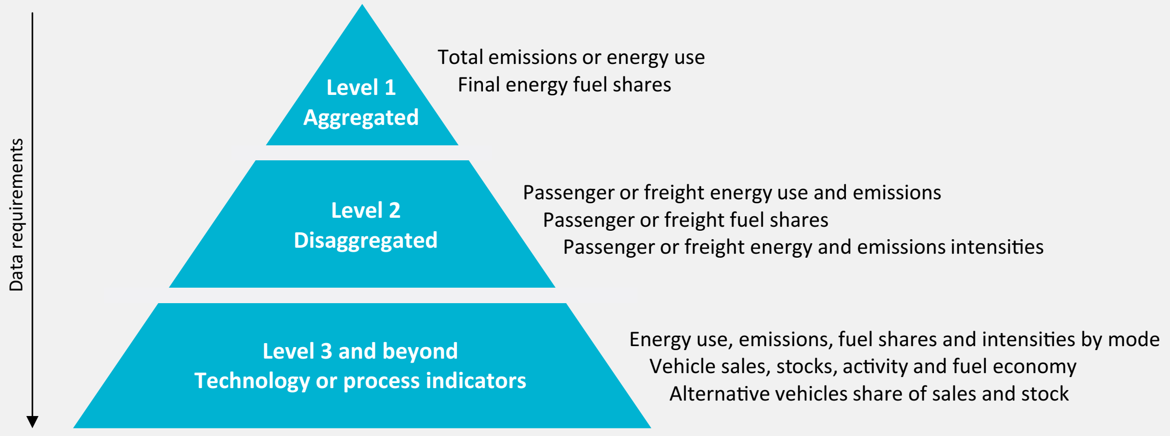
Note: This figure is intended for illustrative purposes, not as a definitive list of indicators.

Key point *It is rarely possible to define a single "true" indicator that fully describes energy use and CO_2 emissions of a sub-sector or a process. A set of indicators is necessary to understand energy and emissions trends.*

Moving to sustainability: Passenger and freight transport energy use and emissions

Energy use in transport is expected to become one of the fastest-growing sectors as global demand for transport, particularly for cars, rises 70% by 2030 and 140% by 2050. Decarbonising transport will require avoiding and shifting demand to more efficient modes,

Figure 2.66 Metrics to track progress in transport



Note: This figure is intended for illustrative purposes, not as a definitive list of indicators.

Key point *Aggregate changes in transport energy use can be better explained and analysed in terms of its components with the proposed hierarchy.*

improving fuel economy of vehicles, and developing advanced vehicles. While significant progress has been made in developing and deploying alternative vehicles such as EVs and FCEVs, these vehicles are unlikely to be adopted widely until after 2030. In the nearer term, therefore, action to avoid and shift transport demand to more efficient modes and to improve the fuel economy of vehicles will have more immediate benefits.

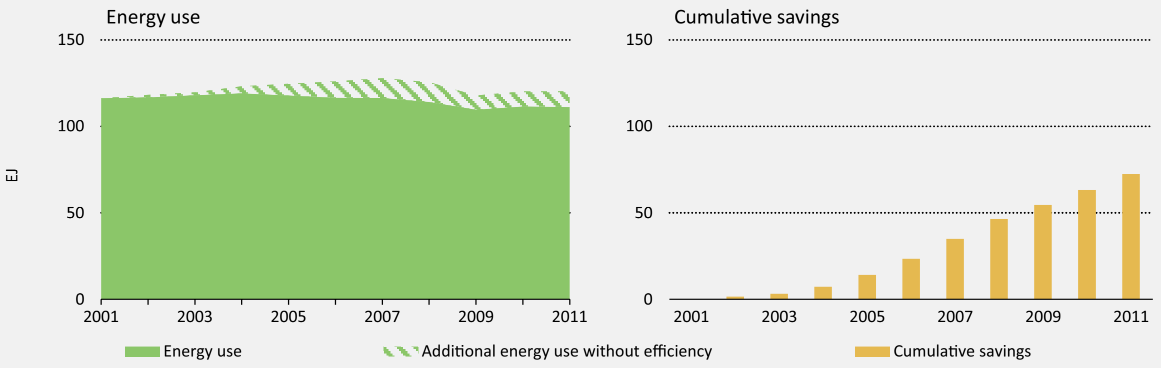
The metrics needed to monitor trends at the global and country level for transport will hence need to cover technology development of advanced vehicles as well as improvements in the energy efficiency of transport (Figure 2.66). Energy efficiency indicators should be developed for both passenger and freight transport, as the drivers and technology options for these two sub-sectors follow different pathways. Countries should combine energy efficiency indicators in transport with indicators to monitor progress at the technology level.

Better understanding the potential contribution of energy efficiency

Energy efficiency indicators on their own cannot be used to predict trends in energy consumption or energy savings. Other factors, such as activity levels and the mix of the activities (structure) at the economy or sectoral level, also influence trends in energy consumption. Understanding how each factor affects energy consumption is essential to determining which offers the greatest potential for energy savings, and the areas that should be prioritised for the development of energy efficiency policies. It is necessary to undertake decomposition analysis to estimate the impact of energy intensity changes (commonly ascribed to energy efficiency improvement).

Energy use in 18 IEA member countries would have seen an additional 9 EJ, or 8% higher, in 2011 (IEA, 2014f), if energy efficiency improvements had not been made (Figure 2.67). These improvements resulted in cumulative savings of 72 EJ over the decade. Such improvements can be translated into reductions in energy-related emissions, showing how important it is in the near term to curb energy use in order to reduce emissions. Energy efficiency indicators can help to quantify the potential contribution of energy efficiency measures to near- and long-term emissions reduction at the national level, thus helping countries to set appropriate targets and monitor progress towards stated goals.

Figure 2.67 Early reductions in emissions through energy efficiency in 18 IEA member countries

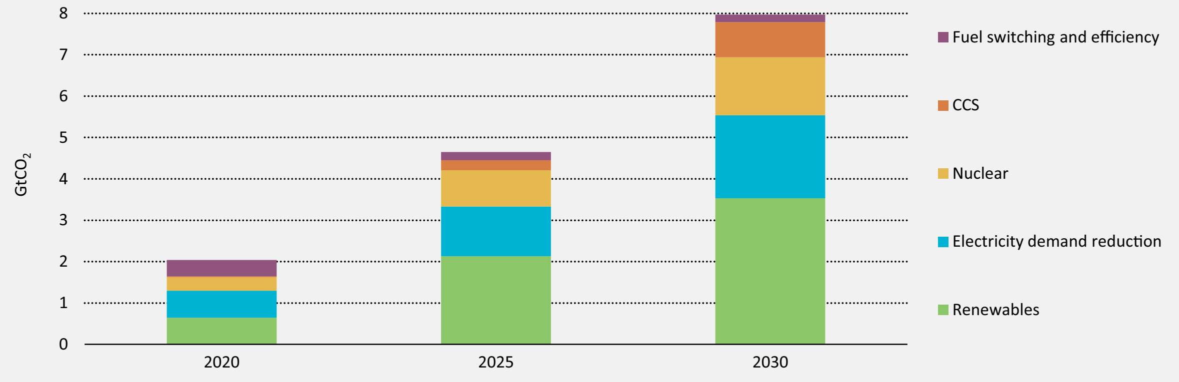


Key point *Energy efficiency has been a consistent and important factor in reducing energy demand.*

Linking energy supply and demand – need for action on both sides

Decarbonising energy supply, particularly in the electricity sector, will be critical to achieving deep energy-related emissions reduction, although this transformation will take decades. Nearer-term improvements in energy efficiency – for example, in the buildings sector – can provide immediate energy and emissions reductions while countries decarbonise the power sector, which globally is the most CO_2-intensive sector. Each 1% reduction in electricity consumption in the buildings sector (equivalent to about 100 TWh in 2012) can help to reduce emissions from power generation by 60 $MtCO_2$,[25] equivalent to an installed capacity of 45 GW of wind power (15 000 turbines) or 23 GW of coal-fired power (46 plants). While tracking progress on power sector decarbonisation through the deployment of zero- or low-carbon technologies such as renewables, nuclear and CCS is important for long-term emissions reduction, impacts of energy efficiency should also be closely monitored given its role in contributing to near-term emissions reduction, as well as other benefits.

Figure 2.68 Saved emissions from reduced electricity demand and power sector decarbonisation



Key point *Electricity demand reduction savings through energy efficiency measures are as important as power sector decarbonisation technologies in reducing overall electricity-related emissions.*

Conclusion

The metrics presented in this section are not an exhaustive list but are intended to illustrate how indicators covering energy supply and demand can be used to inform energy sector goals related to INDCs and to monitor progress towards energy sector decarbonisation. While countries should strive to develop metrics at the highest level possible, simpler metrics have also been identified for countries where data are still limited.

National commitments on climate change require strong action now by energy stakeholders that will reduce emissions in the near term and that will enable more significant, longer-term reductions. To evaluate progress within these different time frames, countries can use these metrics and frameworks to gain a better understanding of how energy is used

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[25] Calculated based on current global emissions intensity of electricity production.

nationally and which specific technologies can reduce energy consumption and decarbonise the energy sector. Capacity building will be needed to help countries improve data collection and to develop metrics and modelling tools to identify and track implementation of ambitious yet attainable goals. IEA expertise in energy statistics and indicators, technology tracking, and energy sector modelling can contribute to the development of these metrics and frameworks, both inside and outside the UNFCCC process.

Technology overview notes

Figures and data that appear in this chapter can be downloaded from www.iea.org/etp/tracking. Enhanced interactive data visualisations are also available for the figures marked with the "more online" ribbon.

The notes in this section provide additional sources and details related to data and methodologies.

Throughout the chapter quoted annual averages are calculated as compound average growth rates.

Renewable power (page 78)

Figure 2.2, 2.3, 2.5 and 2.8: source: data for 2000-20 from IEA (2014g), *Medium-Term Renewable Energy Market Report,* OECD/IEA, Paris.

Nuclear power (page 84)

Figure 2.9 and 2.10: source: Data from IAEA (International Atomic Energy Agency) (2014), PRIS (Power Reactor Information System) database, IAEA, Vienna, www.iaea.org/pris/ (accessed 26 March 2015)and NEA (Nuclear Energy Agency) and IAEA (International Atomic Energy Agency) (2014), *Uranium 2014: Resources, Production and Demand (The Red Book),* OECD/NEA, Paris.

Figure 2.11: source: realised grid connection data from IAEA PRIS database; OECD/NEA.

Construction span from first concrete to grid connection. Grid connection for projects under construction is estimated based on recent public information.

Natural gas-fired power (page 86)

Figure 2.12: 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: Oil-fired power generation is negligible in Germany and the United States (<1%), but represents 14% in Japan (2013).

Figure 2.14: The capacity factor represents the full-load hours a plant was operated as a percentage over a whole year (8 760 hours).

Coal-fired power (page 88)

Figure 2.16: "Other renewables" includes geothermal, solar, wind, ocean, biofuels and waste.

Carbon capture and storage (page 90)

EOR is a closed cycle process which involves injecting CO_2 into older oil reservoirs to increase oil recovery and prolong production. The CO_2 is injected into the reservoir, recovered from the produced oil and re-injected. Some CO_2 is retained in the sub-surface in each cycle, leading cumulatively to the storage of significant amounts of CO_2; however, EOR projects are not necessarily subject to the same stringent monitoring requirements as dedicated storage projects and therefore it is difficult to account for the performance and permanence of the storage.

Figure 2.18: Large-scale projects are defined in accordance with the Global CCS Institute: 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 Global CCS Institute's Asset Lifecycle Model. GCCSI (Global CCS Institute) (2014), *The Global Status of CCS: 2014,* GCCSI, Melbourne.

Figure 2.19: source: BNEF (Bloomberg New Energy Finance) (2014b), Clean Energy Investment Trends, BNEF, London, http://about.bnef.com/tools/ (accessed 19 January 2015).

Private spending represents the publicly disclosed cost of projects including CCS that are in construction or operation and have a capacity equal to or greater than 100 MW in power generation (and all industrial projects). Private spending figures reflect the total cost of a project (i.e. the entire cost of a facility equipped with CCS) with the exception of a small number of cases where cost estimates for the CCS process are publicly available. Grants represent all public funds awarded to projects excluding repayable loads, tax incentives and bonds. All figures shown do not include spending prior to 2005 on CCS projects such as In Salah, Sleipner and Weyburn. Spending in nominal USD.

Figure 2.20: data in USD 2013 prices and purchasing power parity (PPP).

Industry (page 92)

Figure 2.21: Industry totals include feedstock use in the chemicals and petrochemicals sector, and blast furnaces and coke ovens in the iron and steel sector.

Textbox: source: ISO 50001-certified sites information as of end of May 2014, Peglau, R. (2014), Federal Environment Agency of Germany, Umweltbundesamt, personal communication.

Figure 2.22: Industrial energy use per unit of industrial value-added in USD 2013 prices and PPP.

Iron and steel (page 94)

Figure 2.24: 2DS targets for energy intensity in 2020 are, in some cases, higher than 2012 energy intensity. This short-term increase is due to limitations in penetration of energy efficient processes which rely on availability of scrap metal. Beyond 2020, energy intensity decreases again, based on both scrap availability and deployment of new technologies. Energy use includes blast furnaces, coke ovens, iron ore agglomeration processes, steel-making and fuel use allocated to the generation of heat that is produced and used on-site through co-generation systems. Comparisons of this indicator among countries and regions are limited, as there are considerable differences across the iron and steel sector, specifically structure and quality of iron ore. BAT values: coke oven net energy use = 3.7 GJ/t coke; blast furnace net energy use = 10.4 GJ/t hot metal; DRI gas = 10.4 GJ/t DRI; DRI coal = 20.0-25.0 GJ/t DRI; scrap-based EAF = 350 kWh to 370 kWh/t crude steel (1.3 GJ/t crude steel).

Figure 2.25: BOF = basic oxygen furnace, OHF = open-hearth furnace.

Figure 2.26: In this figure only direct CO_2 emissions are considered. Indirect emissions from electricity use are not included. In regions where the EAF process route is prevalent, this can make up a large share of the overall emissions related to iron and steel manufacturing.

Transport (page 98)

Figure 2.31: Total aviation transport energy includes international bunkers.

Well-to-wheel refers to the energy use and 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 impact (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.

Fuel economy (page 100)

Figure 2.34: The growth in non-OECD car markets implied a reduced coverage of markets with fuel economy policies in place.

Electric vehicles (page 102)

Figure 2.35: source: Electric Vehicles Initiative – IEA (International Energy Agency) (2015), *Global EV Outlook 2015*, OECD/IEA, Paris.

Figure 2.36: source: MarkLines (2014), MarkLines Automotive Industry Portal database, MarkLines, Tokyo, www.marklines.com/en/ (accessed 26 March 2015).

Figure 2.37: source: MarkLines (2014), MarkLines Automotive Industry Portal database, MarkLines, Tokyo, www.marklines.com/en/ (accessed 26 March 2015).

Buildings energy efficiency (Page 104)

Figure 2.39: In France, building codes have varied scaling factors based on climate and type.

Figure 2.40: Multiple family (MF) and single family (SF) do not represent the full electricity consumption but rather the building code portion for thermal loads. See IEA Energy in Buildings and Communities (EBC) Implementing Agreement Programme Annexes 56 and 61 for detailed economic and technical data.

Building envelopes (Page 106)

Figure 2.42: source: IEA (2013c) *Transition to Sustainable Buildings: Strategies and Opportunities to 2050*, OECD/IEA, Paris.

Appliances, lighting and equipment (Page 108)

Figure 2.43: source: EES (Energy Efficient Strategies) and Maia Consulting Ltd. (2014), *Energy Standards and Labelling Programs Throughout the World in 2013*, report commissioned by Australia Department of Industry, EES and Maia Consulting.

Figure 2.44: source: SEAD (Superefficient Equipment and Appliance Deployment) (forthcoming), LBNL (Lawrence Berkeley National Laboratory) dataset, personal communication, superefficient.org.

Figure 2.45: EU countries represent the nine largest EU markets; United States data include both boilers and furnaces.

Source: BSRIA (Building Services Research and Information Association) (2015), Condensing boilers market share and forecasts database, BSRIA, United Kingdom.

Co-generation and district heating and cooling (Page 110)

Text box: source: data available for Austria, Estonia, France, Germany, Japan, Korea, Norway, Slovenia, United Arab Emirates. Euroheat & Power (2013), *District Heating and Cooling: Country by Country Survey 2013,* Euroheat & Power, Brussels.

Renewable heat (Page 112)

Figure 2.49: Final energy for heat (FEH) is defined as the direct use of energy for heat plus the use of commercial heat (heat produced and sold to a third party). A more detailed discussion on the methodology and derivation of the FEH indicator is presented in IEA (2014h), *Heating without Global Warming: Market Developments and Policy Considerations for Renewable Heat*, OECD/IEA, Paris. (www.iea.org/publications/freepublications/publication/FeaturedInsight_HeatingWithoutGlobalWarming_FINAL.pdf).

Official IEA statistics do not distinguish between modern and traditional use of bioenergy, as the distinction is difficult to make and currently not possible to quantify. In the absence of data, an estimate is made based on the geography where the biomass is consumed. Modern bioenergy is estimated as biomass consumption in the residential sector in OECD and non-OECD Europe and Eurasia, while traditional use of biomass is estimated as residential consumption in non-OECD regions excluding non-OECD Europe and Eurasia.

Smart grids (Page 114)

Figure 2.53: Regional definitions: 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[26], 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, Slovak Republic, 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, Cape 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.

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[26] 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 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.

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[27], 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, Yemen, Zambia, Zimbabwe.

North America: Canada, Greenland, United States.

source: Navigant (2014), *Smart Electric Meters, Advanced Metering Infrastructure and Meter Communications: Global Market Analysis and Forecasts*, Navigant, Chicago; IHS (IHS Technology) (2014), *Grid-Connected Energy Storage Report 2014*, IHS, Englewood, Colorado.

Figure 2.54: source: EPO (European Patent Office) (2014), PATSTAT (Worldwide Patent Statistical Database), EPO, Munich, www.epo.org/searching/subscription/raw/product-14-24.html (accessed 26 March 2015).

Energy storage (Page 116)

Figure 2.55: source: Platts (2013), *World Electric Power Plant Database*, 2013 edition, Platts, New York, www.platts.com/products/world-electric-power-plants-database.; ECES IA (Implementing Agreement for Energy Conservation through Energy Storage) (2014), Energy storage capacity data, personal communication with Halime Paksoy, Chair.

Figure 2.56: source: India Energy Storage Alliance (IESA) data and estimates, Fernands, S. (2014), "Energy storage: Missing link for microgrids, smart grids and renewables in the US and India", presentation at European Utility Week, Amsterdam, 4-6 November.

Figure 2.57: source: Data for solar thermal storage is for 2012, for Japan 2009, for Sweden 2013 and for Denmark 2014; US DOE (2014b), *2014 Global Energy Storage database*, US DOE, Washington, DC, www.energystorageexchange.org/projects (accessed 26 March 2015).

Hydrogen and fuel cells (Page 118**)**

Figure 2.58: source: adapted from Decourt, B., B. Lajoie, R. Debarre and O. Soupa (2014), *Hydrogen-Based Energy Conversion. More Than Storage: System Flexibility*, SEI (SBC Energy Institute), Paris.

Figure 2.59: source: adapted from US DOE (United States Department of Energy) (2014a), *2013 Fuel Cell Technologies Market Report*, US DOE, Washington, DC.

Figure 2.60: source: adapted from Spendelow, J., J. Marcinkoski and S. Satyapal (2012), *DOE Fuel Cell Technologies Program Record*, US DOE (United States Department of Energy), Washington, DC.; McKinsey & Company (2010), *A Portfolio of Power-Trains for Europe: A Fact-Based Analysis. The Role of Battery Electric Vehicles, Plug-in Hybrids and Fuel Cell Electric Vehicles,* McKinsey & Company, Paris.

Textbox: source: Bonhoff, K. (2012), "Country update Germany", presented at the IPHE (International Partnership for Hydrogen and Fuel Cells in the Economy) Steering Committee Meeting, Cape Town, 3 May.

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[27] 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 GolanHeights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

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Part 2

Mobilising Innovation to Accelerate Climate Action

Technological advances and innovation are core to the vision set out in *Energy Technology Perspectives 2015,* underpinning the modelling work that shows pathways to achieve a low-carbon energy system. Part 2 examines the role that low-carbon energy technology innovation can and must play not only to achieve national and global climate change mitigation targets, but to increase confidence in their feasibility.

Coherent policy and market frameworks that ensure effective support across a range of technologies and through all innovation phases can greatly accelerate the roll-out and impact of low-carbon technologies – particularly when coupled with multilateral collaboration.

The projected energy demand growth in emerging economies, and in China in particular, highlights a critical opportunity for transformation. The interplay of innovative energy technologies and effective policy is examined to highlight the benefits of a systems approach that integrates objectives for economic development, climate change mitigation and energy security.

Chapter 3 **Innovation to Transform Energy Systems** **143**

Energy technology innovation is critical to meet long-term economic, climate and energy security goals in a cost-effective way. With international climate negotiations high on the global agenda, aggressive decisions on energy issues could make 2015 a pivotal year for the credibility of low-carbon growth strategies.

Chapter 4 **Mainstreaming Variable Renewables in Power Markets** **175**

Decades of technological innovation have brought wind and solar photovoltaic to a tipping point: they are now the fastest-growing power generation. Mainstreaming these technologies requires a new wave of innovation focused on system flexibility, underpinned by integrated policy and market frameworks.

Chapter 5 **CCS: Building on Early Opportunities** **207**

Carbon capture and storage (CCS) remains vital to meet long-term global climate change mitigation goals. To stimulate innovation and reduce the cost gap, increased policy action is needed to support research and development and create more market opportunities outside the "sweet spots" where it is already commercially viable.

Chapter 6 **Global Innovation for a More Sustainable Industry** **249**

Progress on low-carbon innovation in industry over the next decade is crucial to achieving longer-term goals. Industry and government can overcome existing challenges, create innovative business opportunities and achieve industrial sustainability by aligning their goals and establishing co-operative frameworks.

Chapter 7 **Low-Carbon Innovation in Emerging Economies** **289**

Emerging economies are at a crossroads: rapidly growing demand for energy and related infrastructure offers the opportunity to lead a low-carbon revolution through deployment of innovative energy technologies. Their choices will either lead to a large-scale increase in global carbon emissions or pave the way towards low-carbon development.

Chapter 8 **Energy Technology Innovation in China** **329**

For China to meet its goal to sustain economic growth and meet increasing energy demand while safeguarding the environment, technology innovation will play a crucial role. Having implemented a substantial policy shift towards a more market-oriented and resilient economy, China is already reaping the rewards of growth in low-carbon energy technology innovation.

Chapter 3

Innovation to Transform Energy Systems

Energy technology innovation – from research to full-scale deployment – is critical to meet long-term climate and energy security goals in a cost-effective way. The year 2015 will be pivotal to set in motion programmes that will increase the credibility of sustainable, low-carbon growth strategies, in support of the United Nations climate negotiations, thereby setting the stage to turn talk into action.

Key findings

- ***Ongoing technology innovation is critical to a rapid, least-cost transition to low-carbon energy systems.*** *Delays in development and deployment of low-carbon technologies could rule out the cost effectiveness of many actions needed to limit global warming to 2°C.*
- ***An interactive and iterative innovation process, aligned with policy and market frameworks is needed to realise the full potential of innovation.*** *Spanning all phases of research, development, demonstration and to large-scale deployment (RDD&D) it must involve multiple stakeholders, capturing feedbacks at various steps to support and practice "learning by research" and "learning by doing".*
- ***A comprehensive understanding of technology developments could strengthen emissions reduction ambition.*** *The United Nations Framework Convention on Climate Change (UNFCCC) could establish procedures to better inform Parties on technology trends, building confidence in available solutions and those still under development. By tracking Parties' activities in technology innovation, the 2015 agreement could also provide signals to scale up this action.*
- ***Uptake of many cost-effective products and processes is stalled by barriers.*** *Creative policy approaches to boost deployment include capturing and valuing the multiple benefits, leveraging research on consumer behaviour, and bundling policies to address multiple barriers.*
- ***Prioritisation of innovation support must weigh both short- and long-term objectives.*** *Addressing barriers for market-ready (or near market-ready) solutions can deliver emissions reduction in the short term. Adequate and consistent research, development and demonstration (RD&D) for earlier stage technologies that show emissions reduction potential are essential to achieve significant cost reductions or performance improvements.*
- ***Multilateral collaboration could provide greater confidence in international innovation efforts needed to achieve global climate goals.*** *The number of multilateral technology initiatives has grown considerably, particularly since 2005, and covers areas such as policy dialogue, expert networks, knowledge transfer and policy or market analysis.*

Opportunities for policy action

- *Base emissions reduction goals for 2025 to 2030 on future technologies, not just today's. Governments should give full consideration to technologies expected to materialise with continued innovation, in addition to the performance and costs of current best available technologies.*
- *Provide stable, goal-oriented support across all phases of RDD&D to facilitate both incremental and radical innovation. Governments should ensure that support continues beyond technology development to address policy and market barriers that typically arise at demonstration and deployment phases.*
- *In the 2015 UNFCCC climate agreement, recognise and encourage actions across all phases of low-carbon technology innovation. Regularly reporting and compiling information on individual and collective efforts in low-carbon innovation will build confidence. It will also foster steps to find new solutions or uptake/adapt existing solutions to national or regional contexts.*
- *Identify short- and long-term technology needs at the global level, and track progress in technology development against these benchmarks. Ongoing evaluation of innovation efforts is needed to assess success, and determine how to best support specific technologies. Such a process would build in flexibility to account for faster or slower progress, as well as the influence of external conditions (e.g. energy prices or macroeconomic conditions).*
- *Scale up financial support for low-carbon technology to levels consistent with the investment needed in the 2°C Scenario (2DS) (currently estimated to be underfunded by at least a factor of 3). Building on existing bilateral, multilateral and international partnerships can accelerate innovation while reducing individual exposure to the financial risks. Strengthening the alignment of UNFCCC technology and finance mechanisms with mitigation goals can improve effectiveness.*

Decarbonising the global energy system to meet long-term climate mitigation goals requires a strategic and staged approach, advancing technology innovation simultaneously on multiple fronts. It is important not to limit the scope of energy technology innovation to RD&D only – but also to include the last D – deployment. Rapid and widespread deployment of mature, readily available low-carbon technologies can enable immediate greenhouse gas (GHG) emissions reduction and lead to ongoing performance improvements and cost reductions. Targeted RD&D are also needed at the beginning of the innovation cycle – but are equally important throughout the entire innovation process – to achieve incremental improvements and create opportunities for the discovery of new solutions across a wide range of technologies over the medium and long term. Ultimately, the objective is technology deployment that will have timely, least-cost and at-scale impacts towards meeting global climate goals.

Deployment is emphasised as even technically sound and cost-effective technologies are not guaranteed to achieve the widespread deployment needed: as they enter the marketplace, numerous non-technical barriers can block their way. This means that in addition to scientific and engineering efforts to accelerate innovation, substantial work is needed in the areas of policy, markets and finance to advance deployment.

Experience shows the need for a range of approaches – on both supply and demand sides – to support technologies at each stage of RDD&D. An integrated policy and market framework can leverage synergies between private and public sectors, thereby setting conditions for uptake of commercially mature, low-carbon technologies. Early-stage technologies that are critical for longer-term decarbonisation face a bigger challenge in reaching necessary levels of deployment. By creating initial markets and delivering incentives for technology development, effective policy can help "push" them through RD&D stages, ensuring that promising, early-stage technologies survive the "valley of death" during the transition from pilot scale to cost-competitive availability. Realising the 2DS requires that the short- and long-term benefits of innovation policy are considered together (Box 3.1).

Box 3.1

Energy technology innovation in Energy Technology Perspectives modelling

Technological advances and innovation are embedded in the modelling work that underpins *Energy Technology Perspectives* (*ETP*). In this modelling, technology costs decline with increasing deployment, following anticipated experience curves.

Recognising that no single technology will solve the energy decarbonisation challenge, ETP models different scenarios to assess how the roll-out of a suite of complementary technologies can meet both short- and long-term goals between now and 2050 (see Chapter 1 for discussion of 2DS results). Importantly, as the modelling also considers policy, market and cost parameters (in line with the International Energy Agency [IEA] technology roadmaps), it ultimately reveals how effective policy can stimulate the lowest-cost path towards the 2DS target.

ETP modelling also identifies which technologies can have the biggest impact on decreasing GHG emissions in the short and medium term. At present, the best opportunities lie in energy efficiency and renewables – both of which already have a range of mature technologies that can be implemented quickly. Rather than needing further technical developments, deploying these short-term solutions requires more emphasis on overcoming policy, market and other non-technical barriers.

Energy efficiency in end-use sectors (e.g. transport, buildings and industry) accounts for over 45% of cumulative emissions reduction between now and 2030 in the 2DS, in part because it is highly cost-effective relative to other options. Renewable energy developments contribute nearly 30% of reductions to 2030. These shares in emissions reduction remain nearly stable to 2050. Power generation improvements, whether through fuel switching or supply-side energy efficiency, between now and 2030 account for nearly 3% of cumulative emissions reduction. But this share decreases to less than 1% to 2050 as these options begin to fall short of more rigorous emissions reduction targets. Switching from coal to natural gas power generation, for example, currently decreases emissions, but as more low-carbon technologies are introduced, after 2025 natural gas power generation begins to have a relatively high emissions intensity.

Conversely, carbon capture and storage (CCS) technology, which is still at the pilot stage for a number of applications, accounts for less than 7% of cumulative emissions reduction to 2030, but this rises to 13% by 2050 as carbon prices increase and wider deployment (particularly in high-carbon sectors such as power generation, iron and steel, and cement production) stimulates a drop in costs. Yet to achieve this long-term potential, CCS requires substantial near-term efforts in RD&D, as well as greater focus on early deployment to gain experience in real market conditions.

A main goal of an integrated policy and market framework is to stimulate both "learning by research" (in RD&D phases) and "learning by doing" in commercial situations. Both types of learning contribute to decreasing prices – and thus to building investment certainty. This vital nexus is highlighted throughout ETP 2015 modelling, analysis and discussion.

Several factors contribute to 2015 being a pivotal year for the transition to a low-carbon energy system. The most overarching is a new international climate change agreement, currently being negotiated under the UNFCCC. The agreement, expected to be signed in Paris in December 2015, will apply from 2020. Action in parallel with the UNFCCC process is also accelerating, with many nations, regions and cities taking unilateral decisions to begin a transition to cleaner energy systems and cleaner end use. As countries develop their positions for the UNFCCC negotiations, and also try to identify their own options for a low-carbon energy transition, they will be seeking to understand what they can expect from energy technology innovation in the coming years and decades – and what actions they need to take to progress technology innovation at both national and global levels.

Global scenarios like the IEA 2DS can help countries assess what is possible – and what is realistic – in their own national contexts, not only in terms of the performance level of current technologies to reduce emissions (including notably costs), but also the improvements that can be expected over time if the innovation system is supported. Policy makers and other energy system actors responsible for mapping out strategies for a low-carbon transition need to know how incremental improvements will affect pricing and understand the role innovative new products and processes will play, as well as what unexpected options could materialise.

ETP 2015 seeks to identify the many ways in which energy sector actors can spur innovation. It explores different stages of energy technology innovation in diverse contexts, highlighting the need to tailor policy and market frameworks in line with stated objectives – whether the objectives are national, sector-specific or linked to progress along socio-economic pathways. Broad-based innovation aspects and sector-specific examples of energy system innovation are highlighted. Each chapter focuses on a specific set of challenges related to stimulating progress along the innovation chain:

- The full-scale deployment phase of the technology innovation or “mainstreaming” of mature renewable energy technologies – particularly wind and solar photovoltaics (PV) – shows the ongoing need for support to remove barriers to reduce emissions through continued and increased deployment (Chapter 4).
- The current status of CCS provides a good framework to explore how early (often niche) deployment opportunities can leverage support and create spillover into other sectors, even while keeping a strong focus on a longer-term target of maximising abatement (Chapter 5).
- Fostering innovation of low-carbon products and processes in industry is essential to meeting global decarbonisation goals and demonstrates the opportunities and challenges across the entire innovation chain of various sectors for global industrial actors (Chapter 6).
- The role of emerging economies is increasingly important in meeting long-term climate goals. Building strong innovation capacities in emerging economies and the resulting benefits of matching the development agenda with sustainability goals is discussed (Chapter 7).

Additionally, like its predecessor, *ETP 2015* recognises the importance of specific emerging economies in the energy transition by including a focused review of one of the IEA key partner countries:

- Numerous strategies, plans and actions demonstrate China’s stated intent to manage the energy-climate-policy nexus, providing an example of how emerging economies can link energy technology innovation and energy policy with their economic growth objectives (Chapter 8).

This introductory chapter outlines the rationale for strategic support across the entire innovation system. It examines the policy actions needed to realise the anticipated technology cost and performance improvements, and presents examples of expected outcomes that technology "in the pipeline" could deliver if adequately supported. Finally, it explores how multilateral collaboration can accelerate technology development, with a special focus on how the 2015 UNFCCC agreement can contribute. In presenting both success stories and known challenges, *ETP 2015* highlights opportunities to accelerate progress towards an economic, secure and clean energy system.

What is energy technology innovation?

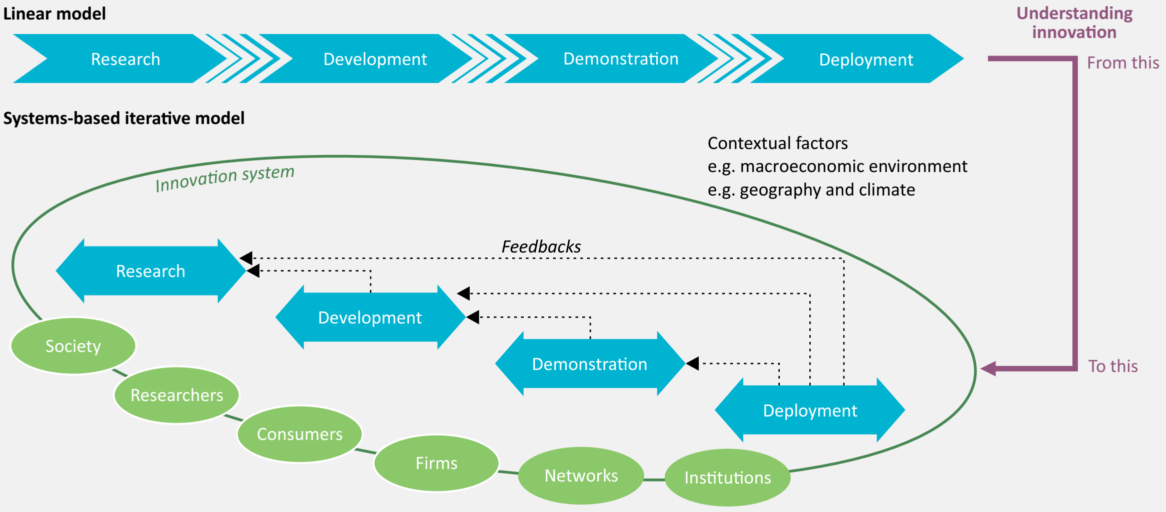
Technological innovation is often described as a linear process comprising four main stages: research, development, demonstration and deployment (RDD&D). While technology innovation does often occur rather slowly through incremental adjustments, this linear approach oversimplifies the relationships among these stages. Innovation in the real world is more complex; few technologies follow a seamless transition from one step to the next, and this model fails to capture many realities that can occur in the process (Gallagher et al., 2012).

Innovation in the energy sector tends to have particularly slow rates, reflecting the fact that technologies tend to be large, complex and built to last for many years. But disruptions do occur, typically caused by factors that can be geopolitical (e.g. the 1973 oil embargo), political (e.g. targets for rapid renewable energy deployment), structural (e.g. demographic changes), social (e.g. a consensus to retire nuclear plants) or techno-economic (e.g. manufacturing cost reductions).

Considering these drivers and the fact that they interact, *ETP 2015* will consider innovation using a systems perspective, which acknowledges that feedback occurs among the different stages of the RDD&D process, and even between various technologies developing in parallel (Figure 3.1). Demonstration projects, for example, can uncover the need for significant new projects to be carried out at the research phase. Feedback from the market and from technology users during the market formation and deployment phases can lead to additional RD&D. When technologies are closer to commercialisation, market competition can prompt additional innovation (IEA, 2013b). A systems view of the innovation process also highlights the importance of external contextual factors such as macroeconomics, geography and progress in other technology areas.

A more systemic approach to innovation also extends beyond the technology-focused "hardware" innovation process to include analysis of actors, networks and institutions. It recognises an interactive process involving a network of firms and other economic agents (most notably users) who, together with the institutions and policies that influence their innovation and adoption behaviour and performance, bring new products, processes and forms of organisation into economic use (GEA, 2012). It includes understanding the people involved in creating and using technologies, and the social and political norms through which they interact. Many of the technologies that become widespread in the 2DS will rely on society adapting to their specific qualities. This could include new routines for using and fuelling vehicles, more individual control over household energy provision, and new industrial practices that will require different regulatory approaches.

Figure 3.1 The evolution of thinking on innovation processes



Note: Figures and data that appear in this report can be downloaded from www.iea.org/etp2015.
Source: GEA (2012), *Global Energy Assessment: Toward a Sustainable Future*, Cambridge University Press, Cambridge, United Kingdom/New York; the International Institute for Applied Systems Analysis, Laxenburg, Austria.

Key point *Innovation is an iterative and uncertain process with feedback loops across all steps; it is influenced by diverse stakeholders and contextual factors in the broader national or global environment.*

ETP 2015 uses “innovation” broadly to refer to energy technology innovation, which has been defined as material and knowledge combined in some novel application, involving energy conversion and/or the provision of a useful energy service (Grubler and Wilson, 2014). It is not only about breakthrough technologies, but includes also incremental improvements of mature technologies and/or novel uses of technologies outside their originally developed application. For clarity, the following table outlines how various terms are used within *ETP 2015* (Table 3.1).

Innovation in the energy system differs in many ways from innovation in other areas, particularly in being relatively slow: technological transitions in energy can span several decades or up to a century. Several factors explain the slow rate of change: capital intensiveness, longevity of capital stock, time needed for learning and experimentation, and clustering and spillovers[1] (Gallagher et al., 2012). Another consideration is that changes to energy supply do not always impact the quality of the service provided to the consumer. Whereas mobile phones brought new freedom to the users of traditional landlines, clean electricity does not provide additional value directly to end users, and biofuel replacements for gasoline do not change the transport service. This lack of a noticeable change in the energy service value proposition for many low-carbon energy innovations could limit the rate of uptake since supporters must be convinced of a less tangible benefit, such as climate change mitigation.

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[1] Clustering refers to transformation in the energy sector arising from combinations of technology; spillover refers to the applications of technologies outside their initial sector/use.

Table 3.1 Definition of key terms used to describe innovation, including energy technology innovation

Key term	Definition
Innovation processes and stages	
Innovation	A process by which ideas are developed into technologies that can be put into practice and continuously improved through a process (iterative in nature) of design, testing, application and feedback from users.
Research & development (R&D)	Knowledge generation through directed activities (e.g. evaluation, screening, research) aimed at developing new or improving on existing technologies.
Demonstration	Construction of prototypes or pilots for testing and demonstrating the technological feasibility and/or commercial viability of new technologies.
Research, development & demonstration (RD&D)	A commonly used grouping of the main pre-commercial stages of the innovation cycle.
Niche markets	Application of a technology in a limited (or niche) market setting, based on a specific relative performance advantage or on public policy incentives; the technology is typically protected in some way from full market competition. Also referred to as "sweet spots" in this book.
Market formation	Activities designed to create, enhance or exploit niche markets and the early commercialisation of technologies in wider markets.
Deployment	Activities to promote widespread uptake of a product or process throughout the market of potential adopters.
Types of innovation	
Incremental innovation	**(also: continuous)** An improvement in performance, cost, reliability, design, etc. to an existing commercial technology without any fundamental novelty in end-use service provision.
Radical innovation	**(also: breakthrough, disruptive)** A novel technology that strongly deviates from prevailing norms and thus often entails a disruptive change from existing commercial technologies and for associated institutions.
Drivers of innovation	
Technology push	**(also: supply push)** Forces that drive the generation of innovation, e.g. by reducing innovation costs.
Market pull	**(also: demand pull)** Forces that drive the market provision of innovation, e.g. by increasing innovation payoffs.
Types of energy technology	
Energy supply technologies	Technologies used to extract, harness or transport primary energy resources (e.g. coal, uranium, sunlight) and convert them into secondary and final energy (e.g. petrol, electricity).
Energy end-use technologies	Technologies that convert final energy into a useful service for end users (e.g. heating, mobility, entertainment).

Source: adapted from Grubler, A. and C. Wilson (eds.) (2014), *Energy Technology Innovation: Learning from Historical Successes and Failures*, Cambridge University Press, Cambridge, United Kingdom/New York.

Why does innovation matter for decarbonisation?

Energy technology innovation is fundamental to the transition to a low-carbon economy. It augments the portfolio of options available and, over time, brings down the cost of achieving global climate change mitigation goals.

In the short term, greater innovation is needed in technology deployment – primarily through renewed actions in policy and markets – to get mature, low-carbon technologies into the market quickly and to keep alive the prospect of limiting temperature rise to below 2°C. The IEA 4-for-2 Scenario (IEA, 2013a) shows that a set of four actions (increasing energy efficiency, reducing inefficient coal use, phasing out fossil fuel subsidies, and reducing methane venting and flaring) can keep emissions close to a 2°C trajectory in the period to

2020 at zero cost to gross domestic product (GDP). Additional IEA analysis (IEA, 2014b; IEA, 2012a) confirms that energy efficiency investments are rising with the support of new and creative finance mechanisms. Yet two-thirds of the potential energy efficiency opportunities remain untapped.

The recent Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report compiled a range of modelling scenarios[2] that explore the importance of technology innovation for energy sector decarbonisation over the long term. This analysis reinforces that the availability and cost of technologies strongly influences mitigation costs, and that the cost of delayed technology action is even more important for more stringent mitigation targets (Edenhofer et al., 2014). The IPCC review found two technologies to be particularly critical to the cost and feasibility of achieving deep emissions reduction: CCS and bioenergy, including the combination of these as bioenergy carbon capture and storage (BECCS).[3] With limited availability of these technologies in the future, some models were unable to find scenarios consistent with keeping global warming below 2°C. When all supply-side technologies were delayed and energy efficiency lagged, no models could find a feasible solution. These findings that delays in technology introduction undermine the overall cost-effectiveness of the 2DS are echoed by ETP analysis (Box 3.2).

It should be noted that energy technology innovation does not take place only in low-carbon energy technologies: traditional high-carbon energy technologies are also still being improved. Innovation in extraction technologies has made additional hydrocarbon resources available at economically viable costs – thereby dispelling the spectre of a near-term peak in oil production. Incremental improvements in the efficiency of coal-based electricity generation technologies can widen the gap in generation costs relative to solar PV and wind generation. In the case of unconventional gas, the combination of RD&D for horizontal drilling technology, high market prices, and supportive policies has reshaped North American gas markets and subsequently global oil markets. In the short term, some climate benefits have arisen with the switch from coal- to gas-based generation. But over the long term, fossil-based generation without CCS technology will become inconsistent with long-term climate goals. The reality is that low-carbon and high-carbon energy technologies will continually compete for RD&D resources. Ultimately, this competition for innovation support will affect the relative cost and performance of low-carbon solutions.

Policies for energy technology innovation

In the context of a clear need for energy technology innovation, policy makers have a central role in the design and implementation of policy frameworks that effectively support the development and adoption of technologies, sometimes even after they have become commercialised. For earlier stage technologies that still need to reduce cost and/or improve performance to become competitive with incumbent approaches, "technology push" mechanisms are most effective (Figure 3.3). At the deployment and adoption phases, "market pull" policies are more effective. This is especially true in the case of many energy efficiency products and practices that are described as having negative costs but still do not achieve optimal levels of market penetration (i.e. it is cost-effective to adopt them under current policy and market conditions, but some barrier[s] stall their uptake) (Box 3.3). Support in these later phases does not preclude further R&D, as feedback throughout the innovation system can yield even further developments.

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[2] The IPCC compiled emissions reduction scenarios from peer-reviewed studies undertaken by various research groups.

[3] Many 2°C-consistent modelling pathways rely on BECCS to generate negative emissions later this century, offsetting an overshoot in emissions in the short term. The IEA 2DS analysis sees only a small amount of BECCS deployment out to 2050. BECCS deployment may be limited by concerns with ensuring stable, consistent quality and sustainable biomass supply in quantities large enough to justify the investment in the capture plant, and by having in place the necessary transport and storage infrastructure for the captured CO_2.

Box 3.2

Increased investment costs of technology delay in electricity generation

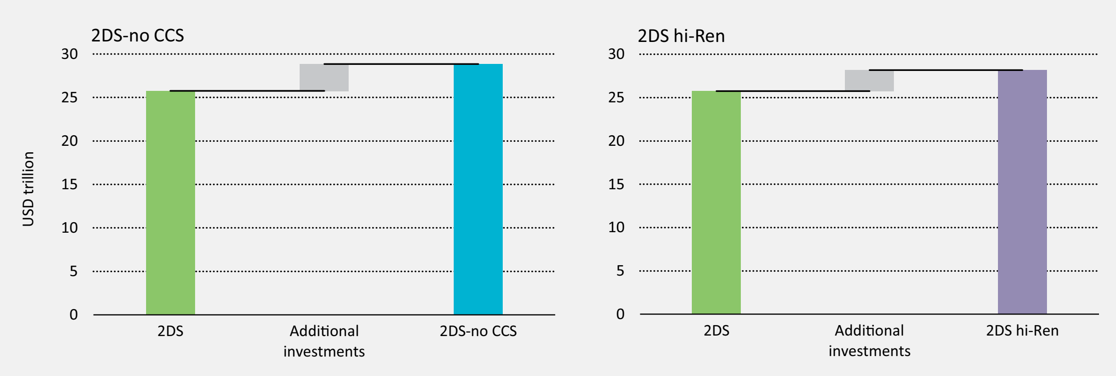
ETP makes a point of assessing the implications of technology delay, which could result from slow progress in any element of the innovation chain. *ETP 2012* explored a series of 2DS variants to test how differing technology assumptions would impact the power generation sector. These Scenario variants were all designed to deliver the same cumulative CO_2 budget,* so different outcomes reflect in different costs, rather than more or less emissions reduction.

One variant removed the option of CCS, as compared with the 2DS in which power generation with CCS provides 14% of electricity. This led to an increase in cumulative investment needs to 2050 of USD 3.1 trillion – i.e. a 12% increase in capital requirements relative to the 2DS to meet the same climate target (Figure 3.2). These higher investment requirements were partially offset by increased fuel savings, moderating the overall cost increase due to the unavailability of CCS to USD 1.9 trillion from 2009 to 2050.

A second variant had a higher share of renewables ("hi-Ren" Scenario), while the potential for nuclear was constrained and CCS development delayed (but not eliminated) so that CCS deployment in 2050 fell to 460 gigawatts (GW) (compared with 960 GW in the 2DS). This scenario resulted in cumulative additional investment needs of USD 2.5 trillion (a 9% increase). Taking into account additional fuel savings resulting from the high-renewables generation mix, the overall costs were USD 2.1 trillion higher than the base case over the same time period.

Figure 3.2

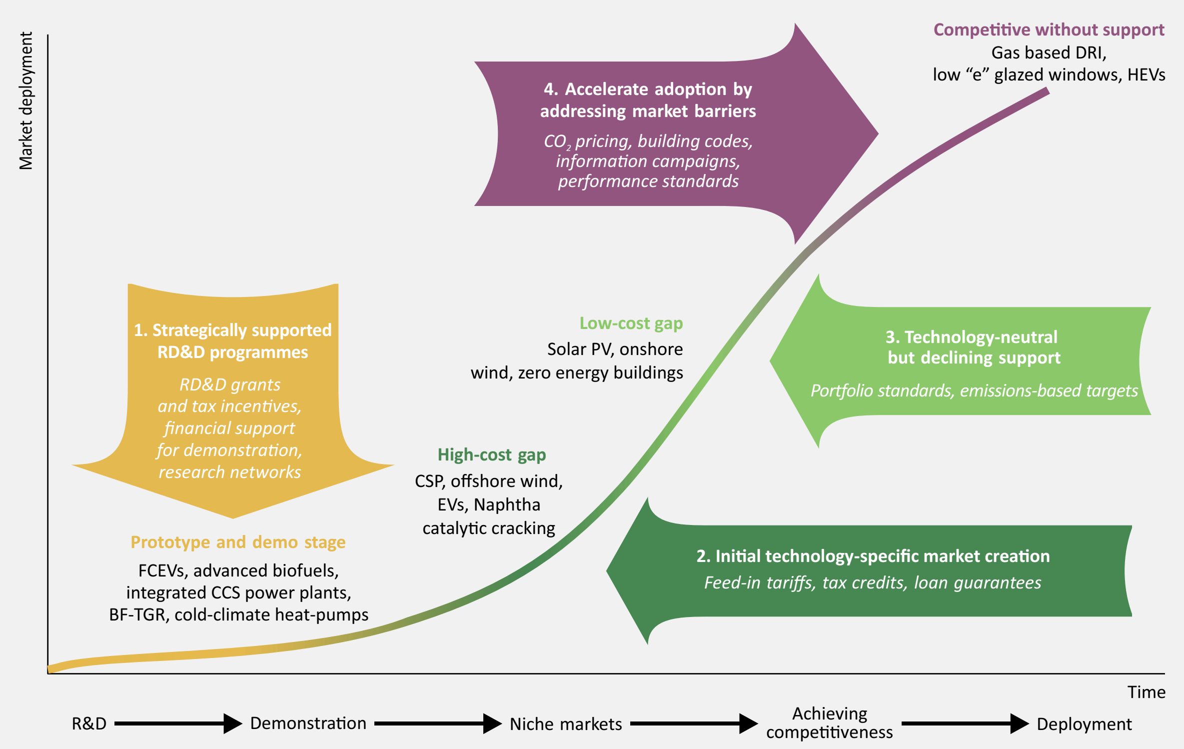
Investment costs of technology delay and unavailability in power generation



Key point *The least-cost pathway to achieving the 2DS includes a portfolio of technologies; if some technologies are not available, the costs of a low-carbon transition can rise significantly.*

* These variants assumed that the power sector had to achieve the same reduction efforts as in the original 2DS. From a systems perspective, some of the required emissions reduction in the variants may also be realised in the end-use sectors, reducing the overall costs of the variants, though these effects were not included in the analysis.

Figure 3.3 Tailoring innovation support to reflect technological and market maturity



Note: EV = electric vehicle; CSP = concentrated solar power.

Key point *Innovation support measures need to be tailored to the maturity level of the technology and the degree of market uptake.*

There are risks that existing regulations or other policies may favour current technologies, despite clear benefits of and technical capabilities for new approaches. Electricity market rules in the United States, for example, have inadvertently prevented electricity storage technologies from participating in ancillary service markets. Two regulatory orders issued to address this barrier have enabled expanded activities to bring new energy storage technologies online (IEA, 2014a).

Similarly, *ETP 2015* will examine how non-technical barriers have influenced wind and solar PV technologies as they have moved from relative technological immaturity (on a cost/performance basis) in early-stage markets to competitive or near-competitive cost levels in large-scale markets (Chapter 4). This transition from RD&D phases towards deployment has prompted the need for a shift in focus from technology and early-stage market support to assessing whether policy and market structures need to be adjusted to enable mainstreaming of these technologies. In the longer term, it is clear that the policy frameworks will need to evolve from supporting the transition to a sustainable energy system to regulating a fully developed low-carbon economy.

Box 3.3 Policy for innovation in technology deployment: The example of energy efficiency

A large gap still exists between the actual adoption of energy efficient technologies and the economically optimal adoption rate: the IEA estimates that only between 20% and 40% of the energy efficiency potential is achieved within each sector (IEA, 2012a; IEA, 2014b). Considering the large role that efficiency plays in the 2DS to achieve emissions reduction, establishing policies to unlock this energy efficiency potential is critical. Codes, standards and labels, subsidies, tax incentives, and financing mechanisms (e.g. energy savings performance contracting) are effective policy instruments to support energy efficiency. Using a variety of instruments may help to identify behavioural levers or cross-purposes, and is more likely to uncover creative approaches to deployment that achieve efficiency improvements while minimising demand on government resources. Some examples include:

- **Identifying and valuing the multiple benefits:** policy packages that include strategies to recognise and monetise the benefits of energy efficiency beyond the energy saved are better placed to evaluate the full impacts of efficiency investment. The IEA counts numerous multiple benefits from energy efficiency such as improved energy security, better health outcomes and higher asset values. New Zealand recently set new policy for building efficiency retrofits, developed jointly by the Energy Efficiency Conservation Authority and the Ministry of Health. *Ex post* analyses showed that almost all of the monetised benefits were linked to improved health (IEA, 2014c).
- **Understanding and leveraging social sciences research:** advances in behavioural economics and psychology are providing insight into how information, framing and programme design influence human decision making. Issues arising include consumer focus on short-term costs, loss avoidance and status quo bias, heuristic decision-making processes, and social context. Japan's Eco-point programme has used information to appeal to social values and change reference points. The programme rewards participants for investing in approved energy efficiency measures through points that can be redeemed as gift vouchers for eco-friendly products, public transport passes and donations. The points established new reference points for participants to gain value and created an element of fun competition among friends.
- **Bundling to enhance policy effectiveness:** policy packages that address different barriers while also improving market and behavioural contexts can amplify efficiency outcomes. Coupling performance standards with labelling and financing schemes, for example, may create stronger-than-anticipated demand for a product, in turn reducing technology costs and creating a positive feedback loop for more efficient products (Brown, 2014). Since 2008, the Canadian province of British Columbia has bundled several policies to support continued improvements of the vehicle fleet. These include a carbon tax (which increases the cost of fossil fuels), subsidies for hybrid electric vehicles (which are more efficient than internal combustion engine vehicles) and financial incentives (to retire older, less efficient vehicles). The bundle of provincial policies also interacts with federal vehicle fuel efficiency standards brought into force in 2014, which aim to improve new vehicle efficiency by 55% by 2025.
- **Forcing technical innovation:** regulations that strengthen over time can drive ongoing improvement. Across 20 different products (ranging from electronics to freight vehicles), Japan's Top Runner Program uses best-performing models to set the standard for future efficiency targets. After five to six years, the existing best-performing model is "downgraded" to having an average efficiency for the product type and new targets are set. This approach raises the average efficiency of all goods, thereby promoting ever-improving efficiency.

- **Using advanced technology to monitor, verify and enforce (MVE):** monitoring change, verifying whether targets are met and enforcing regulations are all important to achieving efficiency policy objectives, but MVE programmes can be costly to implement. Technological advances such as mobile computing and Quick Response (QR) codes could significantly reduce the monitoring and verification costs associated with energy efficiency labelling of consumer products. The development of consumer-level networked energy monitoring devices, which report on disaggregated household energy consumption in real time, could provide a platform for other policy and market innovations to save energy.
- **Being opportunistic:** new opportunities to improve efficiency can surface even when energy efficiency is not an explicit goal on the government agenda. Mexico is converting its television (TV) broadcast system to a digital signal. As a result, older, less efficient analogue cathode ray tube TVs would need a new digital set-top box (STB) to receive the digital signal. Instead of subsidising digital STBs (and adding a new source of energy demand), the government is giving away 14 million new light emitting diode (LED) TVs to low-income households. These new TVs are about 30% more efficient than average models. Thus, predicated on future energy savings and annual subsidy savings of USD 2.54 million, the USD 1.4 billion cost for the TV giveaway will be recouped over time (BN Americas, 2014).

While these types of creative policy approaches at the deployment stage show potential to increase the uptake of energy efficient devices and solutions, they should be seen as an extension of – rather than a substitute for – existing strategies and policies that are already effective. They also require commitment to MVE, in-depth stakeholder consultation and capacity building.

The role of energy efficiency should not be underestimated, even in terms of offsetting some of the negative effects of delays in technology development. The IPCC Fifth Assessment Report (Edenhofer et al., 2014) found that in scenarios with unavailability of CCS and a phase-out of nuclear power, faster energy intensity improvements enabled five of ten scenarios studied to still meet the 2°C goal. Across all scenarios, mitigation costs were roughly halved in scenarios with accelerated energy intensity improvements.

Opportunities for first deployment of a new technology or a new use of existing technologies are referred to in *ETP 2015* as “sweet spots” (similar to the idea of niche markets in much writing on innovation). This refers to situations where the technology is a good fit for a particular application and thrives in a small market space, sheltered from the larger and otherwise hostile commercial environment. Sweet spots have limited potential for wider deployment, but begin to allow the technology to compete with more mature options, thereby gaining much-needed learning-by-doing experience. Once established in a sweet spot, technologies are more likely to attract nurturing resources while growing success (and increased learning) boosts the chance of spillover into new uses and new opportunities. Over time, a variety of such opportunities can gradually advance the technology towards being competitive for mass market applications in the mainstream of the energy system. Examples of sweet spots include offshore wind in Denmark, bioethanol in Brazil and electric buses in China. Another international example is that electric vehicles (EVs) have captured less than 1% of global vehicle markets, but make up more than 10% of the burgeoning car-sharing market.

In addition to the alignment of technology push and market pull policies, low-carbon energy technology innovation will benefit from high-level government support, consistent policy over time, linking of financial and technology goals to overcome financial barriers, coherence with emissions reduction and climate adaptation planning, and strengthening capacity (UNFCCC, 2013). Tailoring support as technologies develop is an important starting point; adapting that support as technologies or approaches evolve keeps up the momentum while limiting support costs and avoiding the creation of "overheated markets". In many attempts to date, such adjustments have been implemented in ineffective ways, with policies tending more towards "start/stop": initial progress is very quick but as deployment costs rise, support is rapidly withdrawn, causing instability to those invested in the market. Start/stop policies increase costs by creating uncertainty for investors who may then need higher returns to meet perceived risks.

Strategic management of the innovation process should include foresight activities and priority setting that will align energy system development with wider national or regional goals. It can also entail activities such as linking industrial policy to export opportunities of products or expertise. Such a portfolio approach for an innovation system will create some overlap but also help to mitigate risk for the ever-changing global energy environment. It builds in flexibility to respond to changes in technology or the broader market. Choosing to pursue a range of low-carbon energy technologies towards a low-carbon pathway can mitigate the risks associated with volatile fuel prices or supply disruptions and uncertainty in the development of specific technologies. Of course, a balanced approach is needed at the national level: very few countries can afford to strongly support innovation across a large number of energy technologies. Aligning resources, capabilities and projected long-term needs creates a more robust strategy for energy supply.

Driving sustainable industrial innovation on a global basis is an essential challenge to meet long-term climate goals (Chapter 6). Innovation to achieve sustainable production practices is relatively new territory with radically different underlying motivations. Product innovation to deliver new services dominates, while process-based innovation targeted at increased yield plays a smaller role. Although many innovation efforts seek to develop new products with reduced energy consumption and lower emissions, much more effort is needed in and across both areas to meet continued growth in material demands with significantly lower emissions. Uncertain economic and policy outlooks, competitive advantage concerns, and the need for innovation risk management are significant challenges. But great business opportunities can be leveraged by identifying solutions that meet both economic and societal objectives.

The increasing importance of finance for decarbonisation

Under the 6°C Scenario (6DS), by 2050 the cumulative energy sector investment needed to meet growing demand without any new effort to limit emissions is USD 105.0 trillion. Achieving the ambitious decarbonisation goals of the 2DS requires an investment of USD 144.6 trillion – nearly 40% more (see Chapter 1 for additional discussion). The additional investments in the 2DS yield a net savings of over USD 60 trillion to 2050 (remaining as net savings even under a 10% discount rate) but require an increased amount of capital.

In 2014, clean energy investment was estimated at USD 310 billion (BNEF, 2015). While this is a positive sign, ending a two-year trend of decreasing investments, this is not enough to meet long-term goals in the 2DS. A substantial challenge is that the relatively new area of low-carbon energy finance must compete in global financial markets against the well-established norms of broader energy finance. Reorienting available investment towards capital-intensive, low-carbon technologies requires new policy support mechanisms.

Despite progress in development and deployment of technology, low-carbon investments can still be viewed as high risk. This can be especially true in emerging economies and developing countries where the largest share of low-carbon technology needs to be deployed through 2050. The perceived risk has in part been merited – especially on the policy side where, even in member countries of the Organisation for Co-operation and Development (OECD), some changes in policy have spooked investors, or where policy support mechanisms (such as the European Union Emissions Trading System) have not developed as expected.

New and targeted mechanisms to attract finance can help to overcome these barriers and lower the cost of financing. The first green bonds[4] were issued in 2008 by the World Bank Treasury and by July 2014, green bond issuances well exceeded USD 20 billion – twice the amount as those issued in 2013 (World Bank, 2014). The Green Climate Fund is expected to become the largest centralised funding vehicle dedicated to climate change solutions. In late 2014, the fund had reached an initial target by surpassing USD 10 billion in commitments from more than 25 countries. Additionally, multinational public-private collaborations, such as the Global Innovation Lab for Climate Finance, are working to design and pilot new financial instruments specifically targeted at mobilising finance for climate-based projects. It will be essential to monitor various efforts to ensure that funding needs for technology innovation are met across the innovation chain, not just at deployment stage.

Evaluating progress

The development of an effective technology solution does not guarantee its commercial success; in fact, the innovation path exposes technologies to many challenges that could end in failure. Policy makers have a responsibility, in this context, to ensure that available support resources are used efficiently and put towards a portfolio of the most promising technologies, and should be accountable for demonstrating the effectiveness of their efforts to support RDD&D. Over the years, many methodologies were proposed to design and analyse energy innovation indicators (Barbosa, 2015; Shell Global, 2014; Think Grid, 2014) and to try to link the scale of innovation support programmes to the progress in energy technology performance, costs and deployment levels. The IEA's Experts' Group on R&D Priority-Setting and Evaluation analysed a multitude of processes aimed at prioritising energy R&D and related innovation funding, but there remains a vast uncertainty in identifying quantifiable causal effects associated with specific innovation support levels (EGRD, 2014). While there are no straightforward approaches to measuring and evaluating progress, various tools can be applied and results combined to get an overall picture. These include learning rates, expert solicitation, and data on patents and RDD&D spending.

As installed capacity grows and the number and size of the commercial opportunities rises, experience shows that costs will decrease. The relationship between installed capacity and costs, known as the learning rate (often shown schematically through experience curves), is formulated as the percentage in cost reduction for each doubling of the cumulative capacity or production. Because they reduce many complex and technology-specific dynamics to a simple factor (the capacity/cost equation), learning rates are a useful metric to evaluate progress (they are used throughout the ETP modelling approaches).

Once a technology moves into the deployment phase, the learning-by-doing rate becomes more important than the learning-by-research rate, which is more associated with earlier phases. Learning-by-doing typically leads to technical improvements (as designers and operators gain familiarity with the technology), efficiencies of supply chains and reduced finance risk. While learning rates are inevitably an oversimplification, they are a useful metric to explore how costs might change with deployment. Over the past decades, the learning rate for learning-by-doing in major energy technologies has been recorded to be around

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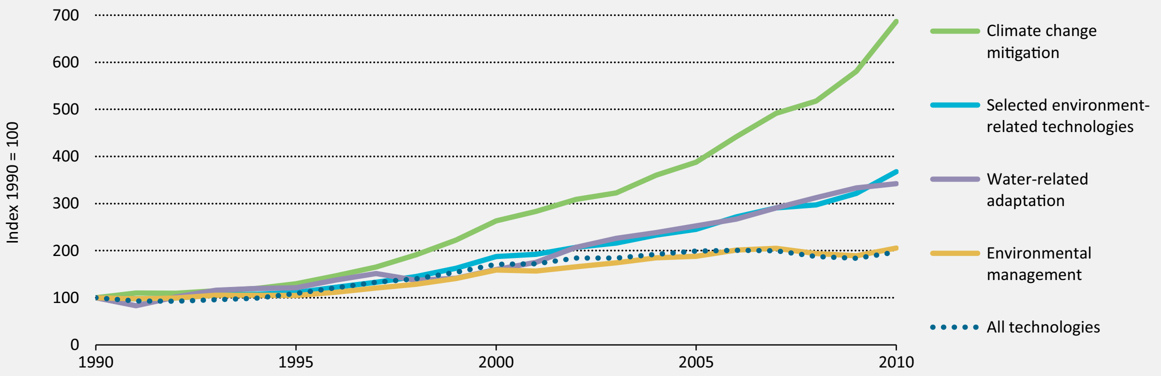
[4] Green bonds are fixed-income, liquid financial instruments that are used to raise funds dedicated to climate mitigation, adaptation and other environment-friendly projects (www.worldbank.org/en/topic/climatechange/brief/green-bonds-climate-finance).

10% – i.e. for each doubling of capacity, the cost drops by 10% (IEA, 2000). The rate tends to be higher for technologies with smaller unit sizes that can be mass-produced (such as batteries or solar PV panels) than for the large unit sizes of nuclear power plants and refineries (for which new plants are more dispersed in time and space). A learning rate of 20% has been suggested for solar PV modules/technologies; for concentrated solar power (CSP), the learning rate is only 10% (IEA, 2014a).

Expert solicitation is another practical way to evaluate effectiveness of RDD&D. This involves asking experts to self-assess their level of expertise in specific technologies and processes, to justify their RD&D priorities, and to identify non-RD&D factors that would affect the future of these technologies and processes. Industry experts are typically well-informed about ongoing efforts in diverse technology areas and can provide useful insights. Rigorous design of such solicitations can increase researcher confidence both in the level of intellectual engagement of the experts and in the external credibility of the results. The selection of experts has a significant impact on the quality of information gathered. Including experts from the private sector, academia and public institutions, as well as experts from different countries and with access to different sets of private information and perceptions, generates more useful information (Diaz-Anadon et al., 2013). The solicitations typically use a range of approaches including evaluation of past innovation successes and failures.

Patent rates of various technology areas also reveal trends in energy technology innovation. Low-carbon energy technology patents filed between 1990 and 2010 have grown by a factor of eight, indicating significant acceleration in innovation investment (Figure 3.4). This is especially significant set against slightly more than a doubling across all technologies, indicating strong progress in clean energy innovation. At the same time, not all innovations or inventions are patented, and measuring the number of patents by itself does not provide an indication of their relative importance and impact. Techniques have been developed to overcome these limitations but they emphasise the importance of carefully interpreting patent-based indicators. OECD countries accounted for over 80% of global patents in climate change mitigating technologies from 2000-11. More recently, patent activity has grown quickly in OECD non-member economies, but since all countries are increasing efforts in this area, the share of OECD non-members is not increasing in the global patent pool (OECD, 2014).

Figure 3.4 Global patent registration rates of selected technologies

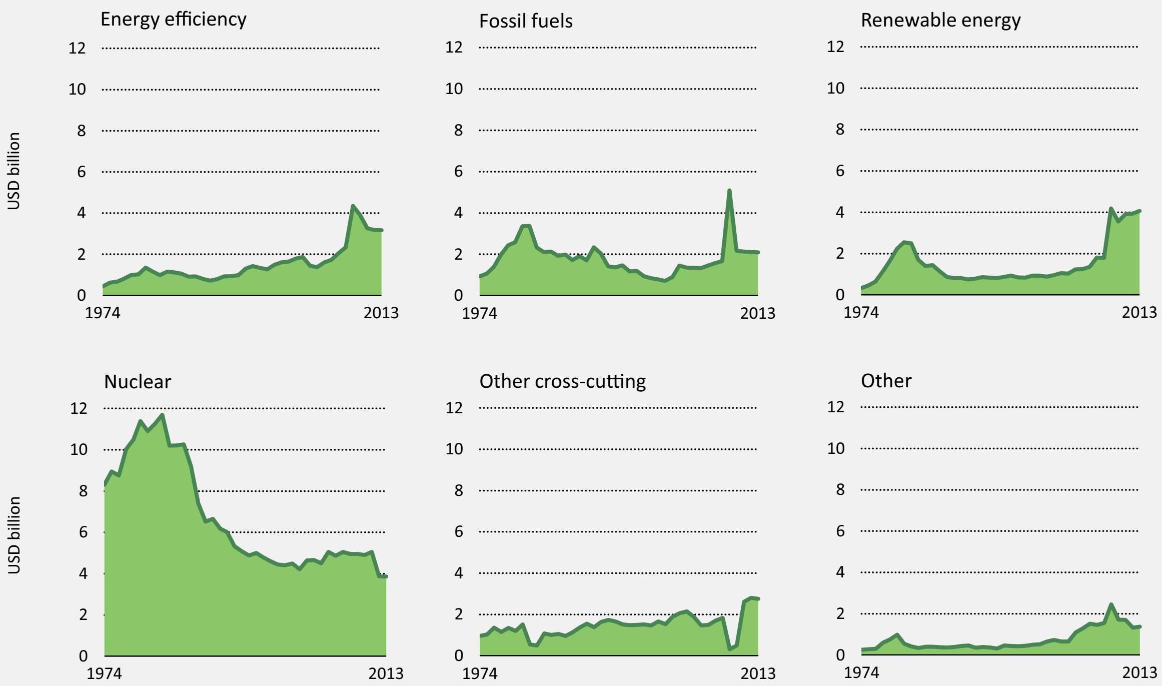


Source: OECD (2014), *Measuring Environmental Innovation Using Patent Data: Policy Relevance*, Environment Policy Committee, OECD Publishing, Paris.

Key point *Based on patent data, innovation in climate change mitigation technologies increased eightfold over the 20-year period from 1990 to 2010.*

Public sector investment in energy RD&D has been growing in absolute terms since a low in 1997, and saw a significant spike from "green stimulus" funding in 2009 (with the exception of nuclear, which had no stimulus funding increase) (Figure 3.5). Post-2009 shows an overall drop, reflecting a return to pre-stimulus growth rates, but with a sustained shift in investments towards renewable energy, which now receives the highest percentage of energy RD&D funding. Again, nuclear RD&D is the exception with a significant drop from 2011 to 2012, and stabilisation at the lower amount over 2013. It must be noted, however, that energy's share of overall R&D has fallen considerably since a high of 11% in 1981, remaining flat at 3% to 4% since 2000. It is estimated that government investment in RD&D should at least triple to achieve the 2DS (IEA, 2013b).

Figure 3.5 Government energy RD&D expenditure in IEA member countries



Notes: *Other cross-cutting* includes energy system analysis and basic energy research not allocated to other categories. *Other* includes hydrogen and fuel cells and other power and storage technologies. More information on IEA energy RD&D statistics can be found at www.iea.org/statistics/.

Key point *Following an investment spike in 2009 due to stimulus packages, recent funding shifts have favoured low-carbon RD&D investments (except nuclear), especially in renewable energy.*

Data on RD&D spending for energy and specifically low-carbon energy is a useful measure, but must be acknowledged as inaccurate on various levels. The vast majority of data available reflects only government expenditures. Private sector data are typically difficult to obtain because of concerns around commercial interest, yet are known to be a much higher level. Thus, with only a small portion of overall expenditures in RD&D available, it is difficult to evaluate how much and where money is being invested. In addition, OECD non-member data are difficult to obtain. The most comprehensive data (from 2008) indicate significant growth in RD&D spending in emerging economies. But direct comparison is challenging as the data and methodology are different: emerging economy data include investments from state-owned enterprises, which in other contexts would be considered additional to government expenditures (Kempener, Anadon and Condor, 2010). Acquiring more, and more comparable, data across all regions is becoming increasingly important as much of the technology deployment needed to meet global climate goals will have to occur in emerging economies.

China, an IEA key partner country, is a particularly interesting case study for low-carbon energy technology deployment in an emerging economy context (Chapter 8). It has aggressive and comprehensive strategic plans for developing a broad range of technologies – across energy and other sectors – with specific aims to show how improving competitiveness can be compatible with innovation in sustainability. China is capitalising on its capability in manufacturing and its growing knowledge base to move from "made in China" to "designed *and* made in China". These efforts do not target only meeting China's immense domestic needs, but reflect the country's global industrial policy. China's aggressive low-carbon innovation and deployment strategies anticipate that future markets will demand environmentally sustainable goods and services.

Steps to build confidence that innovation will deliver

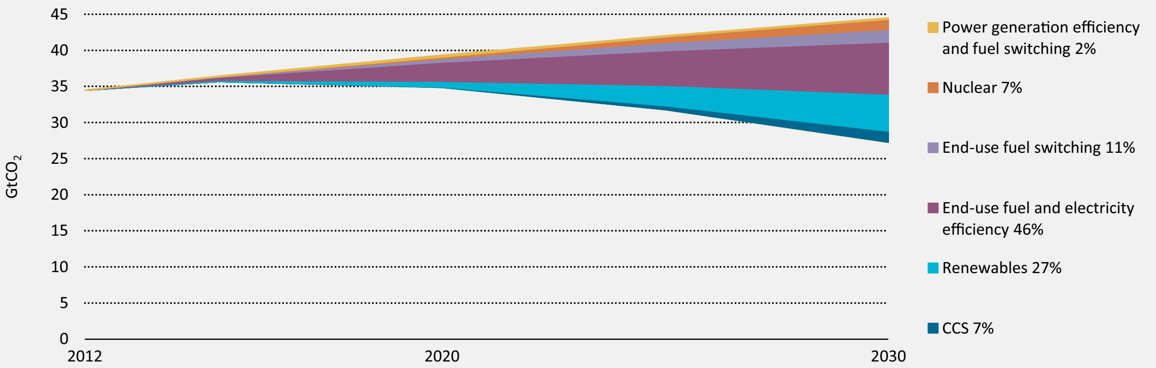
Incorporating expected technology innovation results into national energy sector decarbonisation strategies and climate targets requires more than knowledge of how the innovation chain works and what constitutes good policy for innovation. The cost, performance and implementation options for technologies in the future will depend on what level of innovation occurs globally, so policy makers should consider two further elements:

- **Anticipated future technologies and options for their deployment:** in the current context of RD&D across many low-carbon technology areas, it is important to examine what technologies could emerge by 2030 if levels of support globally are consistent with the levels needed under the 2DS.
- **Opportunities for and benefits of international collaboration:** international – and indeed, cross-sectoral – efforts could provide greater confidence that global aggregate action on technology is in line with global climate goals. International collaboration could also facilitate improved domestic innovation capacity and policy frameworks, thereby providing greater confidence that individual and collective efforts align.

What's in the technology pipeline to 2030?

Examining technologies that are likely to come into competitiveness on the horizon to 2030 covers the *ETP 2015* short- to medium-term period, and also aligns with the first round of mitigation commitments under the current UNFCCC negotiations (discussed later). The mix of technologies that contribute to emissions reduction will evolve over that time, as will their relative shares (Figure 3.6), partially influenced by how quickly individual technologies move along the innovation path through to market deployment, and their costs. Countries must strategise and act on two time scales, quickly creating market pull to aid deployment of mature and commercial-ready technologies while continuing to support RD&D (through technology push) of those that will become viable in the future. They should be assessing technology availability and costs over the full time horizon, not just today's situation, and making efforts to anticipate and remove non-technical barriers.

Figure 3.6 Key technology areas for 2030 emission reduction towards long-term 2050 targets



Notes: $GtCO_2$ = gigatonnes of carbon dioxide. 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 the end-use sectors (buildings, industry and transport) and in end-use fuels (including electricity). End-use fuel switching includes emissions reduction from changes in the fuel mix of the end-use sectors by switching from fossil end-use 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, end-use sectors). Power generation efficiency and fuel switching includes reduction from efficiency improvements in fossil electricity and co-generation (the combined production of heat and power) and heat plants, and from changes in the input fuel mix of the power sector to less carbon-intensive fossil fuels (e.g. from coal to gas). Reduction 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 *Energy efficiency and renewables deployment are needed in the short term to ensure emissions reduction in the 2DS to 2030 is on target to meet long-term climate goals; other technology areas are growing in importance, albeit from very low starting points.*

A concrete understanding of which technologies are "in the pipeline" in the next several years and critical decades is an important aspect of building confidence in innovation outcomes. The known technologies can be grouped into three main categories:

- **Mature and cost-effective, but underutilised, technologies** being those that today have not reached their potential, despite technological maturity and cost-effectiveness.
- **Technologies transitioning towards advanced stages of deployment** being those technologies that are progressively approaching widespread cost-competitiveness, sometimes being cost-effective under specific conditions. Technologies progressing through this stage exhibit declining costs, if support is adequate to sustain deployment.
- **Improved performance of technologies** being those where improved function or changing targets for performance enhancements is opening increased opportunities for the application of technologies from demonstration to deployment stages.

The technologies that are most important to given countries will vary widely based on national and regional context. Based on the above categories, *ETP 2015* briefly highlights several technologies that might define the low-carbon storyline over the next 5 to 15 years, being the most promising to deliver near-term emissions reduction. The selection below is in no way an exhaustive list, and other technologies are covered in much more detail in other chapters.

Mature and cost-effective, but underutilised technologies

Passenger light-duty vehicles (PLDVs) currently consume slightly more than 40% of total transport energy demand with high associated emissions, making this is a primary target for action – even though decarbonising transport is particularly challenging. The Global Fuel Economy Initiative (GFEI)[5] has set an ambitious yet realistic target to cut by half the fuel consumption of new PLDVs by 2030 (compared with 2005). Global average fuel economy of conventional cars should then reach 4.2 litres of gas-equivalent per 100 kilometres (Lge/100 km), a target that aligns with the *ETP* 2DS. Progress seen over the last eight years is at a significantly lower rate than required. OECD countries have demonstrated higher fuel efficiency improvement rates, improving fuel economy at an annual rate of -2.6%. OECD non-members show encouraging signs, but their slow progress of only -0.2% is concerning – particularly as future car market growth will be strongest in these countries (Table 3.2). In 2005, the OECD non-member economies accounted for roughly 30% of the global passenger car market; just eight years later (2013), their share had increased to over 50%.

Table 3.2 Global and regional fuel economy evolution of light-duty vehicles compared with GFEI target

	Fuel economy (Lge/100 km)				Annual change			Required annual change	
	2005	2010	2013	2030 target	2005-10	2010-13	2005-13	2005-30	2013-30
OECD	8.6	7.3	6.9		-3.1%	-1.9%	-2.6%		
Non-OECD	7.3	7.4	7.2		0.1%	-0.8%	-0.2%		
World	8.3	7.4	7.1	4.2	-2.4%	-1.4%	-2.0%	-2.7%	-3.1%

Note: The 2030 target and required annual change refer to 2DS and GFEI.
Source: IEA/GFEI (2014), *International Comparison of Light-Duty Vehicle Fuel Economy: Evolution over 8 Years from 2005 to 2013*, OECD/IEA, Paris.

Although almost 30% of the analysed countries in the GFEI study exceeded the targeted fuel economy improvement rate between 2012 and 2013, the high growth of the least-efficient vehicle markets slows down global progress. Markets with stringent fuel economy policies in place (such as the European Union, Japan and the United States) show the highest improvement rates, illustrating that aggressive targets can be achieved if the right measures are adopted (IEA/GFEI, 2014).

Building envelope technologies, such as insulation, high-efficiency glazings and air-sealing, determine the amount of energy needed to heat and cool a building; optimising the envelope can keep heating and cooling loads to a minimum. A high-performance building envelope in a cold climate requires just 20% to 30% of the energy required to heat the current average building in the OECD countries. In hot climates, the energy savings potential for lower cooling demand are estimated at 10% to 40%. Overall, more than 40% of the savings expected in heating and cooling energy demand under a low-carbon scenario can be directly attributed to improvements in the building envelope (IEA, 2013c).

An important first step in improving the energy efficiency of the global building stock is to establish and enforce stringent building codes, including minimum energy performance for new and refurbished buildings. In some countries, new buildings will last well over 100 years; as retrofits are expensive, urgent action is needed to ensure that high-performance building envelopes rapidly gain market share and quickly become the standard for all new construction globally.

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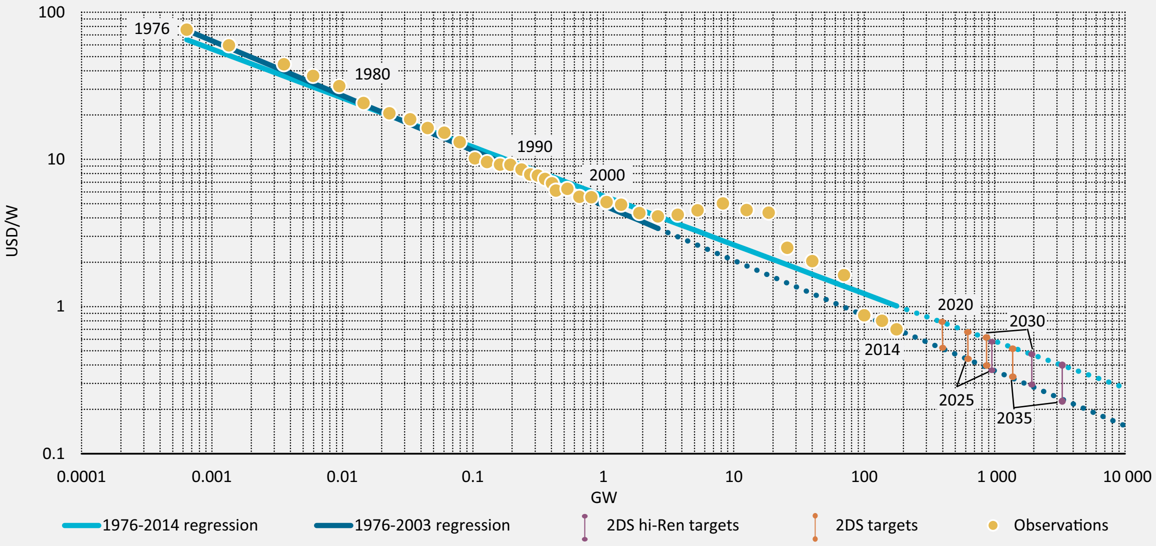
[5] GFEI is a partnership that promotes the potential of a substantial but attainable improvement in vehicle fuel economy as a contribution to the debate on how to meet goals for climate change, energy security and more sustainable mobility on a global basis (www.globalfueleconomy.org).

Many of the approaches to reducing energy consumption and emissions from buildings are cost-effective and have short payback periods. But deployment rates are not progressing as needed to meet 2DS targets.

Technologies transitioning towards advanced stages of deployment

Solar PV modules have a well-documented experience curve since the late 1970s, showing a 20% drop for module costs at every doubling of capacity (Figure 3.7). Based on this experience, additional capacity installed will yield further cost reductions; thus, in a high-renewables scenario (2DS hi-Ren), a global market that accelerates deployment will make solar PV competitive in more markets at an earlier time. Balance-of-system costs[6] for solar PV is another area of increased effort. As module costs decrease and account for a lower percentage of total system costs, reductions in various other system components become more important.

Figure 3.7 Experience curve for PV modules, and extension to 2035 in the 2DS and the 2DS hi-Ren



Notes: W = watt. Yellow dots indicate past module prices vs. PV cumulative capacity. Orange and purple dots are projections in the 2DS and 2DS hi-Ren scenarios, respectively. The light blue line assumes a continuation of the historical learning rate, a 20% percentage reduction in price at each doubling of cumulative capacity. The dark blue line assumes an accelerated price-reduction trend where the learning rate is about 23%, which is the rate observed from 1976 to 2003. Price data for the period 2012-14 is consistent with the extrapolation of the 1976-2003 trendline, suggesting that costs between 2004 and 2011 might have been lower with an adequate supply of purified silicon.

Key point *Based on a proven progress ratio, the cost of PV modules could drop by 50% or more by 2035.*

As solar PV costs decline further, non-technical barriers will become more important. In emerging economies, growing familiarity with the technology, build-up of local capacity and the creation of a stable, supportive policy framework will stimulate further adoption at prices similar to lowest levels found globally. At present, installed cost differences can

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[6] Balance-of-system costs refers to the non-PV module components of a PV system such as racking, inverters and other hardware.

be significant even in OECD countries: in Germany, for instance, the per-watt cost of a PV system is half of that seen in the United States. In the absence of a carbon price, solar PV is not yet the lowest-cost electricity generation technology; it does, however, provide a hedge against the risk of price increases in fossil fuels, allowing energy companies to compile more robust energy portfolios at the same return rates (IEA, 2014a).

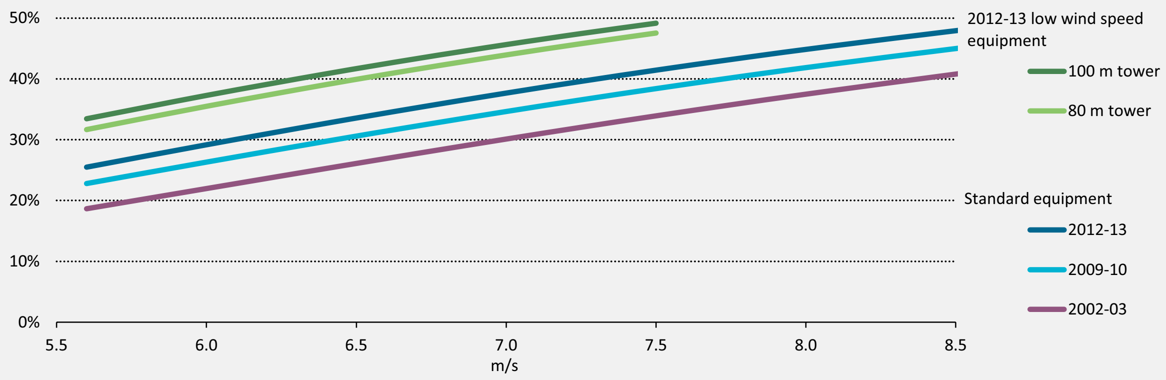
Battery electric storage has been challenging to develop and deploy at scale, but the next 15 years will likely see increased adoption of small-scale batteries with PV systems. Battery technology itself has greatly improved in recent years. To 2030, the technology's prospects are most likely to improve in volume and niche deployments. Several studies project a deployment over the next ten years of 40 GW to 55 GW (Colthorpe, 2014), most of which is in distributed PV with a small capacity, on-site battery. Utility-scale storage will also be deployed in other areas, primarily to provide ancillary services to electricity systems (e.g. for frequency regulation, load following).

Such developments in grid-ready battery storage are closely linked to the growth in throughput of battery manufacturing. In 2013, 40 GW of lithium ion battery capacity was manufactured for portable applications; spillovers from these sectors are helping reduce the costs of EV batteries. Some studies have put the per-kilowatt-hour cost of an EV battery at USD 200 by 2020; some manufacturers may already be rapidly approaching this number (Leuthold, 2014).

Improved performance of technologies

In **wind technology,** the general trend in turbine design has been to increase the height of the tower, lengthen the blades and boost the power capacity. On average, however, turbines have grown in height and rotor diameter more rapidly than their power capacity. This decrease in the specific power (the ratio of capacity over swept area) has considerably pushed up capacity factors for the same wind speeds (Figure 3.8). Reducing the energy cost has been the primary driver of this evolution, which might also have positive implications for easier integration into electricity systems.

Figure 3.8 Capacity factors of selected wind turbines



Note: m/s = metres per second.
Source: Wiser, R. (2012), "Recent developments in the levelized costs of energy from U.S. wind power projects", presentation to IEA Wind Task 26, Paris, February.

Key point *Advances in turbine design over the last ten years have led to significant increases in capacity factors, allowing generation at lower wind speeds.*

This trend has also led to the emergence of rotors designed for lower wind speeds, having even smaller specific power (with high masts and long blades in relation to generator size) and even higher capacity factors. This allows installation of wind turbines in lower wind-speed areas, which are often closer to consumption centres than areas of higher wind resources. This practice lowers the potential for opposition and conflicts associated with wind, as it avoids installation in areas that are sensitive for environment and landscape integration (seashores, mountain ridges, etc.) (IEA, 2013c).

Advances in blade design, often with better materials and also advanced control strategies, have contributed to increased yields from the turbines relative to their installed capacity. Since 2008, the share of gearless or direct-drive turbines has increased from 12% to 20%. Other design variations being pursued include rotors downwind of the tower and two-bladed rotors. Offshore wind turbines are evolving from the earlier "marinised" versions of land-based models towards dedicated offshore turbines of increased size, exploring different substructures such as jackets and tripods. Further design improvements are anticipated.

Table 3.3 Attributes defining a selection of commercially operating projects using CCS technologies

Start year	Project	Sector	Steps in the CCS chain deployed	Primary product cost increase	Commercial foundation	Social/ political foundation
1972	Val Verde, United States	Gas processing	Capture, injection	Low	CO_2 sales (EOR)	
1978	Searles Valley, United States	Electricity/ chemicals	Capture	Low	CO_2 sales (800 tCO_2/day for soda ash)	
1996	Sleipner, Norway	Gas processing	Capture, injection, monitoring	Low	CO_2 tax, technology development	Technology leadership, climate commitment, fossil fuel revenues
2000	Great Plains, United States; Weyburn, Canada	Refining (coal-to-liquids)	Capture, transport, injection	Low	CO_2 sales (EOR)	
2013	Lula, Brazil	Gas processing	Capture, injection	Low	CO_2 sales (EOR)	
2013	Port Arthur, United States	Refining	Capture, transport	Low	CO_2 sales (EOR), public grant, tax credits, technology development	Climate action, technology leadership
2014	Boundary Dam, Canada	Electricity	Capture, transport, injection	High	CO_2 sales (EOR), public grant emissions standard, regulated utility rates, technology learning	Climate action, low-cost coal resource

Notes: EOR = enhanced oil recovery; tCO_2 = tonnes of CO_2. For a full list of projects see table 5.1.

The innovation journey for **CCS** is under way: it is viable in several regions and applications where actors have focused on aligning costs, policy and commercial opportunities (Table 3.3). These initial CCS applications are primarily in industry including hydrogen production, natural gas processing and biofuels production. As climate mitigation actions become more important to the global commercial landscape, these early opportunities will expand in number, market size and geographical extent. Each new project, regardless of context, will provide important lessons that can be used to improve the performance of subsequent generations of technologies and to support their implementation.

CCS has been highlighted as an essential technology in the bid to decarbonise the global energy system. Significant progress has been made recently, but not to the scale expected by many in the industry. A near-term acceleration of technology development and demonstration is needed, not to reduce emissions significantly in the short and medium term, but to build knowledge and ensure the technology is available in the long term.

More in-depth analysis of innovation in CCS technology is found in Chapter 5, which focuses on three key areas:

- early opportunities in certain sectors and regions where CCS technology and emissions abatement costs can be most easily borne
- technological changes with the potential to reduce costs and improve performance of CO_2 capture for electricity generation
- ways in which innovation could help keep CO_2 storage costs low as a proportion of total CCS costs.

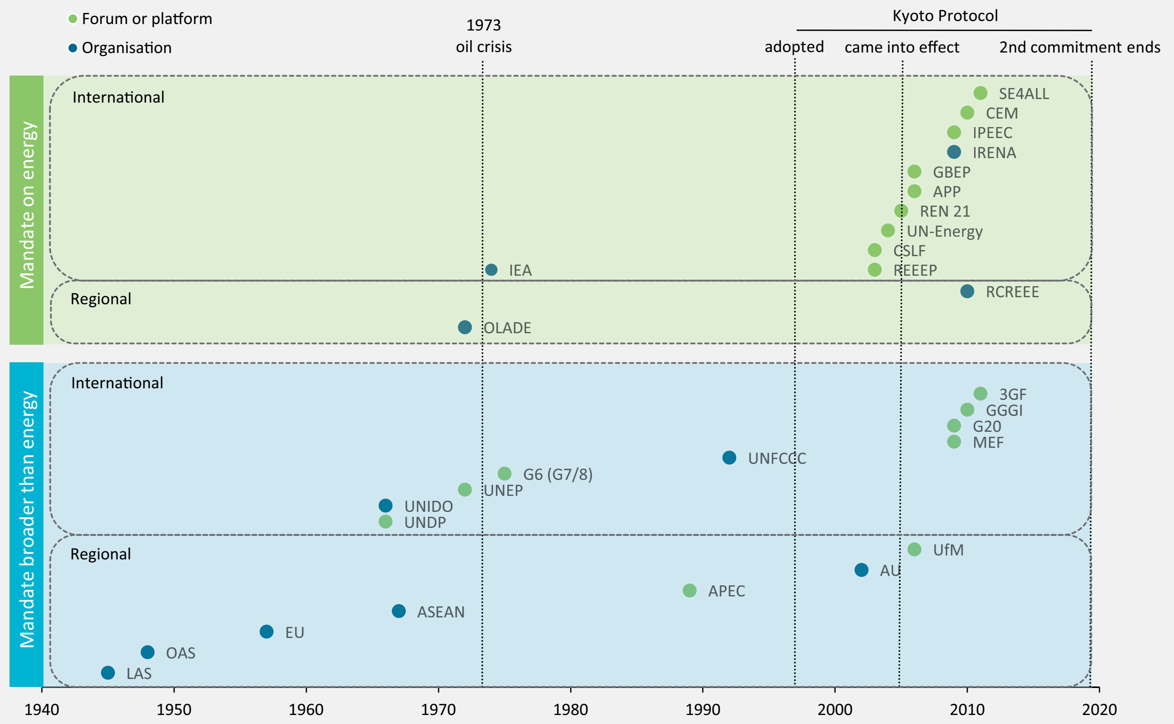
Multilateral technology collaboration

Most of the technological progress that took place during the last century was based on large closed-door research and development programmes kept under tight control until the commercialisation phase (termed "closed innovation" by the American economist Henry Chesbrough) (Barbosa, 2015). Changes brought about by the globalisation of the economy, and the pace at which technology innovation is expected and needed, have brought more and more cooperation between various types of innovation stakeholders in what is now known as "open innovation". In this context, it is expected that multilateral technology collaborations will play an important role in the transition to sustainable, low-carbon energy systems by accelerating technology development and building partnerships, and by increasing capacity to enable faster and more nationally appropriate dissemination of technologies as they develop. These co-operative arrangements focused on low-carbon energy innovation can be driven by non-climate goals, and take place in parallel to the UNFCCC process.

The IEA recently conducted a survey of existing multilateral initiatives that promote deployment of low-carbon technologies. The number of initiatives has grown considerably – now standing at 28 – particularly since 2005 (Figure 3.9), often building on long-standing efforts such as the IEA Implementing Agreements (Box 3.4). Recent developments include cross-cutting initiatives such as the Clean Energy Ministerial, as well as technology- and sector-specific initiatives, such as the Carbon Sequestration Leadership Forum. While there is considerable variation in the legal structure of these initiatives, recent additions have tended to be founded on political declarations or non-legally binding terms of reference, rather than being more formal legal agreements. This gives increased flexibility to the partners, but also raises the risk that activity could diminish if political priorities shift. There has also been a trend towards efforts on individual technologies being addressed as part of a "whole of energy system" umbrella, rather than as stand-alone activities.

Most of the initiatives studied have established networks of experts or stakeholders, who can engage in policy dialogue or undertake activities aimed at knowledge transfer (e.g. capacity building or raising awareness), and policy or market analysis. The past five years show a trend towards greater participation of major emerging economies, including through development of sustainable energy programmes within a range of existing initiatives that have broader mandates beyond the energy sector (such as the G20 and the Asia-Pacific Economic Cooperation [APEC]). This has led to increased multi-directional learning, with OECD non-members sharing their best practice experiences with OECD countries. This differs from the past, which had a more exclusive focus on the transfer of knowledge from OECD members to OECD non-member economies; the new approach is consistent with the growing role of OECD non-member economies as leaders in a range of low-carbon energy technologies (IEA, 2014d).

Figure 3.9 Multilateral initiatives undertaking low-carbon energy technology activities



Notes: For simplicity, sub-initiatives are not shown here. For example, the UNFCCC is included, but the UNFCCC's Climate Technology Centre and Network is not shown separately. For an explanation of acronyms in the above figure, see Annex B.

Key point *A growing number of multilateral initiatives provide a basis for fostering energy technology innovation, highlighting the importance of co-ordination to avoid dilution of effort.*

An examination of what is needed to support the scale-up of low-carbon technology innovation in emerging economies is found in *ETP 2015* (Chapter 7). Large increases in low-carbon technology deployment worldwide can be achieved only by rapidly improving domestic innovation and absorption capacity across all countries. Emerging economies are well placed to lead the urgently needed low-carbon revolution in OECD non-member economies by manufacturing and deploying foreign technologies, adapting foreign technologies to local contexts, developing new technologies that are suited to local energy resource endowment and further deploying these technologies. This presents great opportunities for both OECD members and OECD non-member economies.

Each country's capacity to make the low-carbon transition will depend on its capacity to innovate, and to adapt and absorb new technologies developed elsewhere. For many developing countries, building capacity to absorb and adapt existing technologies will be a priority. The Global Innovation Index 2014 highlighted a global innovation divide, with high-income countries filling the top 25 rankings (Cornell University, INSEAD and WIPO, 2014). Countries' capacity to innovate will be influenced not only by technology-specific policies, but by economic and social environments, from intellectual property rights frameworks to economic structure and education systems (Cornell University, INSEAD and WIPO, 2014).

Box 3.4

The multilateral energy technology initiatives of the IEA

In addition to preparing its own analyses on energy technology, the IEA supports international collaboration on technology RDD&D and information dissemination through the energy technology initiatives (formally organised under the auspices of an Implementing Agreement). Functioning within a formal IEA framework, these technology initiatives provide a convenient mechanism for multilateral collaboration, research and analysis on energy technologies between IEA member countries, non-member countries, businesses, industries, international organisations and non-governmental entities.

Established in 1975, 2015 marks the 40th anniversary year of this mechanism. Some 80 technology initiatives have been created over time, with 39 currently operating. More than 6 000 experts representing 54 countries, 310 organisations, and four multilateral organisations worldwide contribute to these activities in the areas of efficient end use, fossil fuels, fusion and renewables. Over the past 40 years, participants in these groups have examined more than 1 600 topics in the energy field through applied research, testing, expert networks, databases, workshops and scientist exchanges.

Key outcomes from these initiatives include policy recommendations; international standards; models; life-cycle assessments; technology case studies; best practice guidebooks and manuals; databases; and, in several instances, pilot or demonstration projects.

Technology innovation and the UNFCCC process

Linking national and global activities is increasingly important, as under the new climate agreement currently being negotiated under the UNFCCC, countries will self-determine their contributions to GHG mitigation, rather than being expected to meet externally imposed or negotiated targets. In this bottom-up framework, each country's perception of the feasibility and cost of a low-carbon transition will affect its level of ambition. Over time, the success (or otherwise) of innovation efforts will influence how successful countries are in reducing emissions at affordable costs, and therefore how quickly mitigation ambition can be scaled up in the future.

The UNFCCC process is one example of an international initiative that has a limited role in directly driving technology development, but can provide strong signals to scale up that action. The UNFCCC identifies technology – along with finance and capacity building – as one of three critical "means of implementation" that underpin achievement of countries' mitigation and adaptation goals. By 2014, 78 countries had undertaken country-driven Technology Needs Assessments through the UNFCCC process. A new Technology Mechanism was established in 2010, comprising the Technology Executive Committee (TEC) (which provides advice on strategic and policy issues to the UNFCCC process), and the Climate Technology Centre (CTC) and its associated Network (which aims to build technology co-operation, development and transfer through a network of local partner organisations and national focal points).

The UNFCCC sets common objectives for its 195 parties to achieve "stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system," but does not include specific emissions goals for individual countries. The UNFCCC's Kyoto Protocol (signed in 1997) set binding emissions limits for those developed countries that chose to participate. However, by 2020 the Kyoto Protocol commitments will cover only approximately 10% of global emissions (IEA, 2013a). By contrast, the new climate agreement will be applicable to all countries, and is being designed to enable countries to set the contribution they make in accordance with their own national circumstances. These nationally determined contributions will be supported by internationally agreed frameworks for issues such as measurement and reporting of emissions and achievement of goals.

One important element of the 2015 climate agreement will be to recognise and encourage action that countries are taking on low-carbon innovation, while clearly acknowledging that many of these actions may be delivered through partnerships and other co-operation mechanisms established separately from the UNFCCC process. Collecting and compiling information on countries' individual and collective levels of effort in low-carbon innovation (that resulting both from the UNFCCC process and from other activities) and technologies needed for adaptation could help build confidence that technology is "on track", and that ambitious mitigation and adaptation goals are therefore realistic. This applies both to technology needs for the 2020-30 time frame and to those with long-term benefit whose development needs to be supported in the near term. The CTC could play a role in compiling information on levels of national innovation action (in both low-carbon and high-carbon energy options), or this information could be requested in countries' biennial reports or national communications to the UNFCCC, and compiled by the UNFCCC Secretariat. There are multiple ways that the UNFCCC process might further support acceleration of technological innovation (Box 3.5).

The adequacy of collective global action on low-carbon energy technology development could also be compiled and reported outside the UNFCCC process, for example through the IEA annual *Tracking Clean Energy Progress* report (a regular feature of *ETP*). This would shine a spotlight on gaps and opportunities, and signal where greater action is needed. Climate processes including the UNFCCC could use such assessments of global innovation as a basis to invite countries to step up their efforts if necessary, and to ask countries to report on how they intend to do so. In this way, reporting of information into the climate process could help drive greater action on innovation.

Box 3.5

Options for low-carbon energy innovation in the UNFCCC 2015 agreement

A range of measures could be taken within the UNFCCC context to provide greater visibility and impetus to low-carbon energy innovation. It is important to stress that any national or global goals or targets for technology development should complement GHG reduction goals, not be seen as an alternative. Climate negotiators could consider a number of options:

- Set a collective short-term global goal for clean energy RDD&D levels, to provide a benchmark for national efforts.
- Discuss and address the TEC's key messages, which analyse ways to accelerate innovation and barriers to enhanced technology collaboration.
- Include regular reporting of RDD&D efforts to the UNFCCC, as part of biennial reports or national communications. The IEA has developed reporting methodologies that could assist in this process.
- Compile national information periodically to assess aggregate effort in key innovation actions (e.g. RD&D investment, deployment rate of a basket of key technologies), and track this against levels consistent with the long-term global emissions goal. This compilation could be undertaken by the CTC, the UNFCCC Secretariat or potentially an outside agency such as the IEA.
- Invite the CTC to report, ahead of countries setting GHG mitigation targets in each (say five-year) period, on whether technology progress is ahead/behind what was envisioned in the previous period.
- Highlight long-term technology needs as part of long-term emissions reduction goals. The ability to make deep reductions in GHG emissions by 2050 (or reach net-zero emissions in the second half of this century) will depend on innovation. Linking long-term mitigation goals to timely technology progress could focus greater attention on technology actions.
- More closely link the UNFCCC's technology and finance mechanisms with mitigation goals, so that all countries have the means of implementation to achieve ambitious goals.
- Provide financial support to all stages of technology innovation through the UNFCCC's financial mechanisms such as the Green Climate Fund, not only deployment of mature technologies.

Recommended actions for the near term

Accelerated technology innovation – including aggressive deployment of proven solutions – will underpin the transition to sustainable, low-carbon energy systems. As policy makers set national emissions reduction goals for the next 10 to 15 years, information on the potential outcomes from technology innovation (both over this time frame, and to 2050 and beyond) can build greater confidence in committing to ambitious decarbonisation goals. Equally important to confidence-building is gaining a better understanding of the level and nature of global support necessary to drive innovation systems, which brings up the need for mechanisms to track whether this activity is taking place at the required scale.

This chapter's analysis reasserts the IEA long-standing message on the importance of establishing the right policy and market framework conditions and incentives for technology innovation, including well-designed and predictable RDD&D programmes, along with tailored, adaptable market instruments and new business models to support deployment as technologies mature.

Governments need to develop systemic approaches to innovation – tailoring initiatives across the different stages of RD&D and then changing their approaches and mechanisms as technologies move into market formation and deployment phases. At these end stages, stronger collaboration with the private sector is needed to create market pull. Initial market creation occurring in parallel with ongoing R&D to improve technologies is often needed to progress as quickly as possible. A lack of or unpredictable support from policy and markets across these stages of innovation will result in increased uncertainty of success and higher rates of failure.

Prioritisation of resources put towards innovation must consider both short- and long-term objectives to achieve long-term climate goals. Governments play a key role in stimulating development efforts to ensure the pipeline of solutions is robust and diverse, and in removing barriers to enable deployment as technologies mature.

Governments should individually and collectively focus on three specific areas of innovation support. First, they should scale up financial support for low-carbon innovation to levels consistent with the 2DS investment needs, building on existing bilateral, multilateral and international co-operation frameworks. Second, they should share best practice on policy and market frameworks for innovation support to enable rapid implementation (and adaptation where necessary) of initiatives that build investor confidence. Third, they should actively participate in high-level initiatives to ensure institutional continuity and consistency of measures, as well as close collaboration among implementers, policy makers and other stakeholders.

Ongoing evaluation of innovation efforts in technology and in reforming policy and market frameworks is needed to assess success and determine how to best bolster specific technologies. Flexibility is needed to take into account faster or slower progress, as well as the influence of external conditions such as fuel prices or macroeconomic conditions.

In the context of the 2015 UNFCCC agreement, governments could work together to undertake several concrete actions. Countries could agree to track and report their energy RDD&D actions to stimulate greater innovation that could reinforce even more ambitious mitigation goals. New approaches should be sought to capture RDD&D data from emerging economies and from the private sector, taking into consideration the need to protect proprietary information for the latter group. The UNFCCC process could also focus sharper attention on global technology needs and achievements; tracking global progress in key technologies, for example, could help to inform countries' mitigation target setting. The UNFCCC's Technology Mechanism could also be used to greater effect by more closely linking it with overall mitigation goals and with the UNFCCC's finance mechanism.

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Chapter 4

Mainstreaming Variable Renewables in Power Markets

Technology innovation and policy have made wind and solar photovoltaics (PV) the fastest growing power generation technologies. But their cost structure, combined with inherent variability, challenges traditional system operation and investment strategies. Mainstreaming these technologies calls for a new wave of innovation, focused on enabling technologies to boost system flexibility and market frameworks that deliver investment certainty and operational efficiency.

Key findings

- ***Wind and solar PV will require an integrated and well-designed market, policy and regulatory framework to unlock innovation (especially deployment) consistent with the 2°C Scenario (2DS).*** *Continued technology innovation will need to focus not only on wind and solar PV, but also on enabling technologies to increase the flexibility of power systems.*
- ***Such a framework needs to deliver on three challenges that wind and solar PV share with other low-carbon technologies:*** *unlocking investments in capital-intensive technologies, overcoming existing lock-in of carbon-intensive generation and effectively pricing externalities.*
- ***Two additional challenges are specific to wind and solar PV:*** *ensuring operational efficiency at large shares of variable and distributed generation, and securing sufficient investments in flexible resources.*
- ***Experience has shown that success depends on adapting frameworks to the maturity of wind and solar PV deployment markets and respective general power system context.*** *Where the need for investments in power generation is large ("dynamic systems") rapid growth and cost-effective grid integration can be achieved more easily than where investment needs are lower ("stable systems").*
- ***Ultimately, an integrated policy, regulatory and market framework for reaching the 2DS may require convergence across liberalised and regulated markets.*** *In liberalised markets, policy instruments will need to support investment certainty in low-carbon technologies. Where systems remain highly monopolised, the priority is to increase transparency and ensure fair grid access for low-carbon generation, while also taking measures to maintain or improve operational efficiency across large geographic areas.*
- ***The profound system transformation needed for the 2DS requires a large-scale change in investment patterns to occur in a timely fashion and at scale.*** *Establishing robust constraints on carbon dioxide (CO_2) emissions (including a CO_2 price) is a core necessity, backed by mechanisms to unlock investment in capital-intensive technologies and overcome lock-in of fossil fuel generation.*

Opportunities for policy action

- *Successfully mainstreaming wind and solar PV into power systems will require a systems approach, focused on securing investments in low-carbon generation and boosting system flexibility.*
- *Constraining carbon emissions (including through effective carbon pricing) is vital, but deploying wind and solar PV at a speed to reach the 2DS requires additional policy instruments to secure investment and continued innovation.*
- *With high capital costs and low operating costs, wind and solar PV require well-designed policy and market frameworks to expose their generation to market price signals while providing investment certainty to keep financing costs low.*
- *Where power market liberalisation has taken place, policies should be formulated to minimise undesired distortions. Market premium mechanisms, which provide additional support but at the same time expose generators to some – but not all – price signals coming from wholesale power markets are promising options.*
- *Where markets are still regulated, governments need to establish clear and transparent grid access rules for new generation and design contracting instruments (such as long-term power purchase agreements [PPAs]) that reflect the value of assets from a system perspective.*
- *Market rules and system operation need to be upgraded, shifting operational decisions closer to real time, balancing supply and demand over large geographic areas, and ensuring a level playing field for demand-side integration and storage participation.*
- *A particular challenge for stable systems is the need to overcome existing fossil lock-in while minimising stranded asset costs; this requires clear and consistent exit signals for high-carbon technologies.*
- *Giving certainty to the future build-out path of wind and solar PV generation will foster critical innovations and investments in flexible resources, particularly in demand-side integration and cost-effective energy storage.*

Wind and solar PV energy technologies have seen tremendous innovation over the past decades. This ranges from improving technical performance while reducing costs across local supply chains to developing techniques to handle the inherent output variability and uncertainty of these low-carbon generation technologies. With these gains in place, wind and solar PV have become increasingly competitive with conventional technologies and moved strongly into the deployment phase of the technology innovation cycle.

Once a technology has moved passed the initial research, development and demonstration (RD&D), market development (i.e. deployment) can be understood in terms of market diffusion theory (e.g. Usha Rao and Kishore, 2009), which assumes an S-curve-shaped deployment pattern: the market grows slowly initially, picks up speed with time and accelerates up to a certain peak, after which it starts slowing down again until it eventually saturates (IEA, 2011a). As for the case of wind and solar PV, as this process progresses, certain deployment barriers may become more significant, signalling the need for specific policy intervention (Box 4.1). At penetration rates of some 5% to 15% in annual electricity generation, electricity produced by variable renewable energy (VRE) sources can be fairly easily integrated into power systems through some well-established best practice principles. But more significant measures and investment may be needed at higher levels of penetration to address issues such as technical integration, impact on existing generation and wholesale market prices (IEA, 2014b).

Wind and solar PV are now expected to make a major contribution to decarbonisation efforts in the 2DS. But to achieve this potential, the current rate of deployment will need to rise significantly in the near future (IEA, 2014c) and in the longer term. Global deployment of wind and solar PV will need to rise from a share of 2% of annual electricity generation in 2012 to 17% by 2050 for wind, and from 0.4% to 9% for solar PV in the 2°C Scenario (2DS), requiring dramatic changes to electricity system investment and operation. In absolute terms, this corresponds to an increase for solar PV from approximately 100 terrawatt hours (TWh) of annual electricity generation in 2012 to more than 3 700 TWh in 2050 – a 36-fold increase. For wind (land-based and off-shore combined) this implies an increase from approximately 500 TWh in 2012 to approximately 6 200 TWh in 2050 – a more than 11-fold increase. In the high renewables variant of the 2DS, which assumes a more constrained availability of nuclear and carbon capture and storage (CCS), the 2050 contribution of PV stands at 3 700 TWh and that of wind to 7 300 TWh.

Moving towards such broad-scale deployment – or more pointedly, "mainstreaming" wind and PV in energy markets – requires yet another wave of innovation, focused largely on enabling technologies (demand-side integration, flexible generation, storage and grid infrastructure) and, most importantly, the overall policy, regulatory and market frameworks of the power sector as a whole. Early experience in this transition confirms the need for integrated frameworks that carefully consider the country context. It has also become evident that different challenges can be expected as technologies move through the phases of inception, scale-up and mainstreaming; as such, the frameworks need to be changed or adjusted in parallel (Figure 4.1).

The first phase for VREs (inception) began in the late 20th century, when a wide range of technologies were supported predominantly with instruments focused on RD&D. As a result of these efforts, wind and solar PV became increasingly mature and became commercially available, at least in some countries.

In the second phase, support policies sought to stimulate market formation, thereby achieving deployment at scale. As markets grew to sizeable levels, important feedbacks prompted additional RD&D efforts, improving the technologies themselves, and also brought to the fore new challenges such as adjusting economic support levels to falling technology costs in order to contain the total cost of policies. Throughout this phase, incremental refinements of support policies were prevalent.

A key aim of this chapter is to highlight tools to facilitate a faster transition through these phases in countries where deployment has not reached scale by allowing countries to leverage the global deployment experience accumulated to date in kick-starting national markets for wind and solar PV. Three high-level considerations are already evident: the country-specific context in which wind and PV will be deployed (see below), the mechanisms available to ensure efficient and cost-effective energy markets (including those to reduce direct support), and the characteristics of the technologies and the level of penetration (which affects how they will interact with the overall electricity system).

Reaching the third phase, i.e. mainstreaming VRE technologies (including, wind and solar PV) into electricity markets in line with the 2DS, will likely require more fundamental changes in the policy, regulatory and market frameworks of electricity systems. Ultimately, what is needed is an integrated framework that addresses five key challenges. Three of these are common to all low-carbon technologies:

- **Pricing of externalities:** the social costs of CO_2 and other emissions need to be reflected in electricity pricing, as such costs will influence investment and operational decisions within the power sector.

- **Unlocking investments in capital-intensive technologies:** with high up-front costs and often very lower operating costs, low-carbon technologies do not neatly "fit" the usual risk-return calculations that underpin investment in power generation assets in liberalised markets. Reducing investment risk is a key factor in unlocking such investments at least cost.
- **Overcome existing lock-in of fossil fuel generation:** decarbonisation implies a radical departure from historic investment patterns, which have focused on carbon-intensive options and comparably lower levels of distributed generation. This implies a large-scale re-allocation of investments to facilitate progress towards decarbonisation in a timely fashion and at scale. In addition, achieving the 2DS calls for the retirement of fossil fuel plants without CCS before the end of their technical lifetime.

For wind and solar PV in particular, two additional aspects are of primary importance:

- **Ensuring operational efficiency at large shares of variable and distributed generation:** the inherent variability and uncertainty of wind and solar PV call for moving operational decisions closer to real time and providing incentives to operate assets in a flexible manner. Moreover, the large number of distributed resources requires more sophisticated approaches to co-ordinate system operation that goes beyond the traditional role of system operators.
- **Securing sufficient investments in flexible resources:** in order to reach the high shares of wind and solar PV cost-effectively, additional investments to improve the flexibility of power systems will be of key importance. This includes enhanced demand-side integration, flexible generation, storage and improved grid infrastructure.

An overarching challenge is that mainstreaming these VREs needs to be managed in two fundamentally different market environments:

- **Stable power systems** are characterised by stagnating electricity demand and relatively low short-term need to replace ageing generation and grid infrastructure. These traits are typical of many OECD countries.
- **Dynamic power systems** have high growth rates in electricity demand and/or face significant investment requirements in the short term, for example to increase overall capacity or replace a large amount of capacity that is retired at the same time. These traits are most often seen in emerging and developing economies (i.e. OECD non-member economies).

As the lion's share of additional low-carbon generation capacity, including wind and solar PV, in the 2DS is deployed in OECD non-member economies (see Chapter 7), understanding the specific requirements of these markets is particularly relevant for mainstreaming wind and solar PV.

Within both stable and dynamic markets, it is important to evaluate how existing structures, which were developed for the characteristics of incumbent – largely fossil fuel – technologies, might create non-technical barriers to broad deployment of wind and solar PV.

This chapter discusses wind and solar PV as an example of a group of low-carbon technologies which have seen significant innovation over the past decades. It will track the evolution of policy support instruments that have been used for creating deployment markets and discuss what is needed to transition to the next level of market maturity. As wind and solar PV share several attributes with other low-carbon generation technologies, some of the considerations are valid across all.

Box 4.1

Changes in policy priorities for different phases of technology innovation and market maturity

The market introduction of novel technologies can be understood as a progression through different deployment phases. While there are always important feedbacks between technology-roll out and continued RD&D, such a simplified characterisation can be useful to establish policy priorities. Three main phases can be distinguished: inception, scale-up and mainstreaming. A short summary of the characteristics of each phase helps to set the stage for discussion in this chapter.

Inception phase

- The first examples of the technology are deployed under commercial terms; experience is low, and skilled human resources may be scarce.
- Support is needed to optimise performance and reduce costs, and to record/disseminate lessons learned from integration and operations in real-world markets.
- As costs may be relatively high, managing overall policy costs may require constraining support schemes to achieve predetermined deployment levels.
- Early learning demonstrates the need to adapt framework conditions to novel technologies; significant non-economic barriers may be uncovered (such as lengthy and unclear permitting procedures).

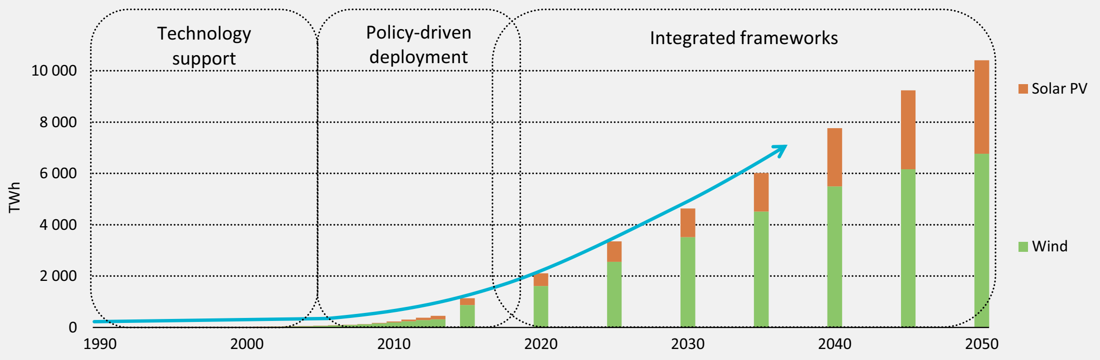
Scale-up phase

- The market starts to grow rapidly.
- As costs may be expected to fall, the policy aim is to manage incentives to ensure that deployment to desired levels is cost-effective.
- New issues regarding overall regulatory conditions may be discovered (such as grid-code requirements, licensing, etc.).

Mainstreaming phase

- The annual market has reached a significant scale; the supply chain is well established and some consolidation of the industry structure may have occurred.
- Investment levels are on par with established technologies, market dynamics are better understood and regulatory frameworks can be adapted to the characteristics of the technology.
- A coherent approach towards the energy system as a whole becomes critical as interactions among new technologies and other system components become dominant.
- The entire policy and market framework may need a more fundamental revision, with a view to deliver long-term decarbonisation at least cost.

Figure 4.1 Three phases of wind and solar PV deployment



Notes: TWh = terawatt hour. Figures and data that appear in this report can be downloaded from www.iea.org/etp2015.

Key point

The priorities to grow and sustain wind and solar PV deployment have shifted from providing technology support to delivering a supportive market framework for reaching the 2DS.

What it takes to deploy wind and solar PV

Provided sufficient natural resource is available, wind and solar PV can be cost-effective contributors to meeting national energy demand and achieving emissions reduction targets. But in many cases it is first necessary to create a level playing field for investments in wind and solar PV, which requires an understanding of the factors that determine a project's feasibility. In general, experience shows that five conditions need to be met for a wind or solar PV project to go ahead:

- **Availability of locally adapted technology and human resources:** technology needs to be available for deployment under country-specific, real-world conditions and sufficiently skilled human resources need to be available for planning, constructing and operating the project.
- **Permitting:** in most cases, a new wind or solar PV plant can be built and operated only after the right permits have been obtained. These can range from spatial planning to environmental impact assessments and specific business licences.
- **Grid connection:** obtaining authorisation for grid connection is a technical pre-condition to selling the generated electricity (off-grid wind and solar PV projects are, of course, the exception).
- **Offtaker arrangements, taking into account both price and quantity:** project developers need to find an offtaker for the generated electricity (except when projects generate electricity purely for self-consumption or for off-grid supply). At minimum, the agreement should determine the price at which electricity can be sold and the quantity of electricity that can be sold. Some offtaker agreements also include provisions about the pricing of deviations between contracted and actual generation (forecast errors, etc.).
- **Financing:** even if all of the above conditions are met, a project will go ahead only if it can attract sufficient financing for development, planning and construction. This aspect is particularly important for low-carbon technologies, including wind and solar PV, which incur the vast majority of costs up-front (i.e. for construction). As such, the cost of financing has a very large effect on the overall cost of the delivered electricity (IEA, 2014a).[1] The aforementioned aspects all contribute to shaping the cost of financing. For example, financing costs will increase if the project is perceived to carry a significant price risk (such as uncertainty of fossil fuel or emissions pricing) or quantity risk (such as load factor risk). Other factors, including country-specific characteristics such as degree of political stability or fluctuating currency exchange rates, can drive up financing costs.

To kick-start and sustain wind and solar PV deployment in a given national market, all of the above areas need to be free of significant barriers. If framework conditions leave a barrier in one of the five critical aspects unaddressed, deployment will either fall short of expected levels, be more costly than necessary – or a combination of both. Understanding the complexity of barriers and the ways in which they interact is equally important (IEA, 2011a).

Market contexts and why they matter

As noted above, the 2DS projects a large share of wind and solar PV deployment in emerging economies – i.e. in dynamic markets characterised by rapidly increasing electricity

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[1] See Chapter 8 in IEA (2014a) on attracting finance for low-carbon generation.

demand, which implies the need for rapid expansion of infrastructure and a short-term need for high levels of investment. The electricity sector in many of these countries is still dominated by vertically integrated, regulated companies.

By contrast, the stable power systems in many OECD countries face sluggish or even negative electricity demand growth, and in the short term require comparably less investments to cover replacement of ageing capacity. Many of these countries have liberalised electricity markets over the past decades.

The simple categorisation into stable and dynamic markets falls short of reflecting many important nuances in terms of both regulatory frameworks and investment needs. Nevertheless, it provides a useful way to distinguish fundamental differences in the following analysis, as the two contexts give rise to diverse opportunities and challenges on the way to establishing an integrated framework for integrating wind and solar PV (IEA, 2014b), and thus meeting the 2DS.

In stable systems, higher shares of low-carbon generation can be achieved only by displacing some of the existing generation. In order to be competitive, the full costs of the new generation must undercut the marginal costs of the existing fleet. Moreover, rapid introduction of low-carbon generation (e.g. via support payments) tends to create a surplus of generation capacity (pre-existing plus low-carbon additions), which may reduce utilisation of plants with higher fuel costs and mute high prices on wholesale markets (which occur during times when electricity demand approaches available capacity). The merit order effect will lead to less costly units satisfying demand; ergo, capacity with higher fuel costs is displaced first and the price on short-term wholesale markets drops. This can be observed in a number of European markets, such as Spain, Italy and Germany. Such low prices can, at some point, trigger the retirement or mothballing of generation capacity, which can raise concerns about security of supply and also impact the plant's business plan and the returns expected by investors.

Conversely, new low-carbon generation in dynamic systems helps fill a supply gap and competes on an equivalent full-cost basis with alternative investment options (such as fossil plants). In fact, dynamic systems have the opportunity to set out on a different path, but only if investment strategies prioritise an integrated approach to low-carbon generation deployment. Adding low-carbon generation in dynamic systems does not put incumbents under the economic stress described above, which can make it easier to aggressively pursue deployment during scale-up and mainstreaming. New grids can be planned and built out, taking into account the nature of the generation, particularly wind and solar PV, thereby avoiding the need for later retrofits.

In many ways, dynamic systems appear to offer an ideal situation to mainstream low-carbon technologies into the system. The main shortcoming is that these systems often lack the level of flexibility contribution that existing assets (e.g. power plants, existing grids) provide in stable systems. As a result, long-term investment strategies for the system as a whole are likely to be relevant at earlier stages of VRE deployment. This raises the importance of planning tools that take into account VREs in longer-term system planning, for informing individual economic agents (companies) or system planners.

Apart from market fundamentals that influence the general climate for investments, the regulatory and market frameworks of the power sector is of key importance for mainstreaming wind and solar PV into the system.

Vertically integrated or liberalised: Another market dimension to consider

Many dynamic power systems are built on a model of vertical integration, while stable systems have typically made the transition to liberalised markets. The underlying structure also influences deployment of wind and solar PV.

Vertically integrated, regulated monopolies: under a model of monopoly provision, the vertically integrated utility enjoys an exclusive mandate to meet the energy demand of customers in a given area: it does not have to compete for customers based on price or the quality of service. Rather, government agencies are tasked with ensuring that the quality meets community expectations and prices are kept at acceptable levels. System operations are typically centralised in the service area, and trade with adjacent areas is usually low. In some cases, independent power producers (IPPs) can generate power to sell to the monopoly supplier.

Planning is carried out in an integrated fashion under this design, with the government or monopoly utility controlling generation additions and grid investments. Construction of new power plants or infrastructure is centrally managed or may be carried out by contractors following a bidding process. When a regulator approves an investment under a monopoly model, the utility passes on the investment cost to all its customers.

Liberalised model with competitive wholesale markets: under this model, generation and sale of electricity is not centrally organised but rather allowed within a regulatory framework to function in a competitive manner. Generators – including those introducing VRE assets – can contract with suppliers of electricity or directly with large consumers, and consumers can negotiate directly with the supplier of their own choosing.

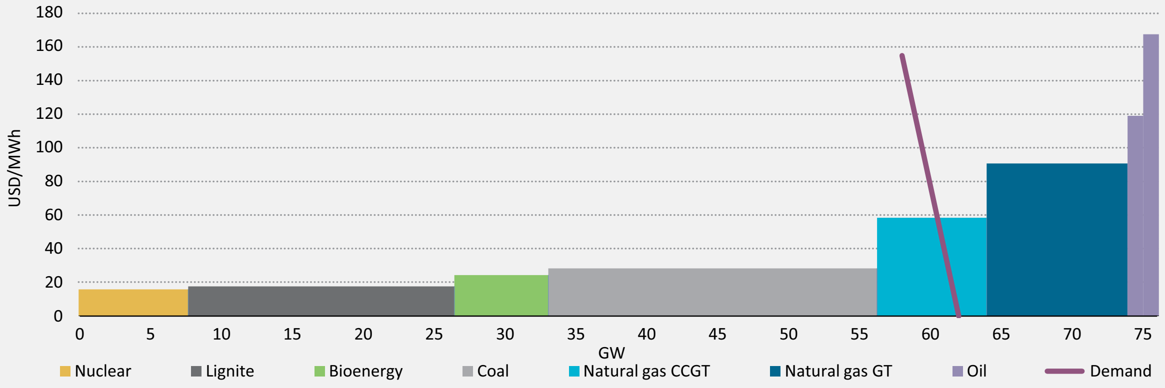
Reflecting the high cost and long life span of power system assets, the wholesale (or bulk power) market structure usually relies heavily on long-term, bilateral agreements (that set prices and quantity) between generators and suppliers and/or consumers. Because actual demand varies (even day to day), market participants generally have the option to carry out short-term trades (to sell or buy a few days or even hours in advance of actual need) from the spot market. The spot market price is of paramount importance in competitive markets, because it provides an important price reference for longer-term markets.

The concept of pricing electricity differently depending on the moment of consumption was originally introduced also to facilitate demand-side response, in which buyers adjust consumption either to save on costs or to reduce overall system demand (IEA, 2014b; Schweppe et al., 1988). The main idea is that the provision of electricity is more or less costly, depending on the demand level, because power plants have different costs for producing a unit of electricity. Whether a unit of energy is considered “cheap” or “expensive” reflects the additional costs associated with producing it – i.e. the short-run costs – as opposed to costs that would have been incurred anyway (such as investment costs and fixed operation and maintenance [O&M] costs). For example, once built, wind and solar PV have no fuel costs, while fossil power stations need to pay fuel costs for each unit of generation. When demand is low, the least-cost units will suffice to cover it; as demand rises, generators with higher operating costs are called to come on line.

As demand patterns vary over the course of a day, spot markets are typically divided into “bidding blocks” that may be hourly, half-hourly or even shorter (more granular) and generators bid to generate in each block. The most costly unit needed to meet demand sets the market price (this is known as the clearing price for that bidding block).

All generators that are called upon to generate receive the market clearing price. Ordering generators according to ascending costs forms the so-called merit order curve (Figure 4.2).

Figure 4.2 Price formation on a spot market during one hour



Note: MWh = megawatt hour; CCGT = combined-cycle gas turbine; GT = gas turbine.
Source: Schaber, K. (2014), *Integration of Variable Renewable Energies in the European Power System: A Model-Based Analysis of Transmission Grid Extensions and Energy Sector Coupling*, Technische Universität München, Munich.

Key point *Prices on electricity spot markets are driven primarily by the short-run cost of the most expensive generation unit called upon to meet demand.*

In theory, the remuneration received on the spot market should also be sufficient to cover the non-variable cost of power plants. When power plants with higher operating costs set the price, plants will receive a market price above the short-run costs. The difference between market price and short-run cost is known as infra-marginal rent. However, since the beginning of electricity market liberalisation, there has been a debate on whether such infra-marginal rents actually suffice to maintain adequate resources on the system (IEA, 2013a; IEA, 2014b). As explained in more detail later in this chapter, reaching the 2DS further adds to this issue.

Electricity grids are the exception in liberalised markets. As the shared “backbone” of the system, they are generally considered a natural monopoly, and the commercial interests of the entity controlling the grid are separated from those of other market participants (this requirement is met by “unbundling”).[2]

Policy lessons from wind and solar PV inception and scale-up

Deployment of wind and solar PV resources is at various stages in different countries. Thus, there is good value in exploring the wealth of experience already gained in developing and implementing policy measures that proved effective in the inception and scale-up phases. Much of the early learning occurred in OECD countries with stable power systems, but more

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[2] Unbundling can be achieved in different ways; see IEA (2013b) for details.

recent lessons can be drawn from experience in dynamic systems such as Brazil and China. This short survey of approaches emphasises the need to adapt policies for different country contexts and different stages of deployment.

Options for policy support

Renewable energy support policies can be roughly categorised according to whether they influence deployment levels by altering prices investors are exposed to (price-based approach) or by mandating a certain quantity of energy or capacity (quantity-based approach).

Price-based instruments can increase deployment by reducing the cost for renewable energy projects from an investor perspective or providing investors with increased revenues to ensure cost recovery. The overall quantity of deployment is determined by investors. Available price-based instruments include:

Feed-in tariffs (FITs) guarantee the generator of renewable electricity a certain price per kilowatt hour (kWh) at which electricity is bought. The tariff is set over a long period of time, commonly 20 years. Note that the tariff is fixed during the entire period of support (sometimes indexed to inflation). Tariff adjustments are made only for new plants. FITs usually include a number of very favourable conditions for renewable energy project owners such as guaranteed connection to the grid, compensation if output cannot be fed into the grid, or no requirement to forecast generation on a project level. A FIT is a standardised, long-term PPA.

Contracts for difference (CfDs) are similar to FITs in that they provide a standardised, long-term PPA for renewable energy projects. The most important difference is that under a CfD, generated electricity is sold directly on the market. If market revenues fall short of a predetermined price (strike price), investors receive additional compensation such that market revenue and support payments equal the strike price. Conversely, if market revenues exceed the strike price, investors reimburse what is surplus to the strike price.

Market premiums are intended to complement revenues generated on the standard electricity market by paying investors according to the amount of electricity they generate or the amount of capacity they build. Premiums can take a variety of different forms (fixed, variable, per energy, per capacity) but all share the basic idea of complementing standard revenues in a way that ensures sufficient investor confidence.

Tax incentives or credits are often used to reduce the cost of renewable energy projects from the perspective of an investor. Mechanisms include reduced tax rates or waiving certain taxes for equipment or revenues from energy sales. Tax incentives can also be given by reducing tax liabilities per unit of generated electricity; this is the case for the production tax credit in the United States. Tax incentives may also take the form of accelerated depreciation of renewable energy assets.

Direct cash grants/rebates can be used to reduce investment costs and so improve returns for investors. Under cash grant schemes, renewable energy project developers get back a percentage of the investment costs in cash. This payment effectively lowers the price that project developers incur.

Quantity-based instruments follow a different logic. Here, a party, e.g. an energy supplier, is obliged to purchase a certain amount of renewable energy or capacity. In this case, the overall deployment quantity is fixed and prices are determined by the cost of projects needed to comply with the obligation. Quantity-based instruments are:

Renewable portfolio standards (RPS) set a target share or total amount of energy generation from renewable energy sources for electricity producers or suppliers. Obliged entities may then procure renewable energy by directly developing projects or by entering into a PPA. RPS build on the assumption that the obliged producer or supplier has sufficient opportunities to build or purchase renewable energy directly. Where this is not the case, a quantity obligation can be combined with trading of green certificates (see below).

Quotas with tradable green certificates (TGCs) work by setting a specific amount of electricity that needs to be covered by generation from renewable energy sources. This obligation is usually imposed on electricity suppliers. In order to allow for meeting this obligation more efficiently, a market is established for certificates that are issued for each unit of green electricity that is generated towards meeting the quota. The certificate market is thus an additional market that is based on the idea of separating the actual power and its "greenness". The electricity component is remunerated in the same way as non-renewable electricity, for example via the wholesale power market. TGC schemes usually include a fine that the entities under the obligation have to pay if they fail to buy enough certificates. In most cases, this penalty rate determines an upper bound for the value of certificates.

Centralised procurement via a government or public body can be used to contract a certain amount of renewable energy or capacity. This approach is usually implemented by organising auctions to contract a predetermined quantity while the price is set in a competitive bidding process. Auctions may contain specific requirements (e.g. shares of local manufacturing, details of technological specifications, maximum price per unit of energy). The bidders with the best offers are selected and can go ahead with the project. Usually the parties sign a long-term contract (PPA).

Policy mechanisms can also be categorised according to how they are financed. This has traditionally been achieved either by an additional charge to electricity consumers (FITs, CfDs, market premiums, RPS, TGCs), via payments through the general budget or dedicated government funds (cash grants and rebate systems), or by accepting reduced tax revenue (tax incentives and credits).

The selection of each policy, regulatory or market instrument depends on local context. For example, a market premium system or a contract for difference requires the existence of a wholesale electricity market to generate a market price signal. Conversely, RPS without certificate trading are only a viable option in cases where the obligation can be reasonably met by a single entity. Past experience with the impact and cost-effectiveness of support instruments have highlighted that more than the choice of instrument, the overall policy package (including implementation details) drives success or failure of the framework. This notwithstanding, it is possible to derive some general lessons for policy design depending on the maturity of the local market. In addition, there has been a degree of convergence between price- and quantity-based systems.

Inception phase

Effective policy approaches for the inception phase should target a combination of the five deployment criteria described above (see section "What it takes to deploy wind and solar PV"). The most successful policy packages have focused on priority areas of the inception phase such as underdeveloped supply chains, lack of experience with deployment under commercial conditions and low levels of technological maturity. Another priority is to establish a clear roadmap that builds investor confidence by showing how policies will support the market introduction and expansion of technologies, as long as performance and cost targets are achieved. Germany's multi-pronged approach during the early inception stage of the solar PV market illustrates such an approach (Box 4.2). The way in which Germany has moved through the various market stages will be examined throughout the chapter.

Box 4.2

Germany's policy approach for solar PV in the inception phase

Germany's success in setting an initial policy environment that brought solar PV through the inception phase demonstrates the importance of a comprehensive policy package. Key elements included:

- a capital grant of up to 70% of eligible installation costs to reduce the direct up-front technology costs
- provisions to streamline permitting, for example by waiving most permitting requirements for residential rooftop PV
- a mandate for distribution grid operators to connect new installations in a timely manner and to enable cost recovery via general grid fees
- guarantee of a fixed price per unit of energy generated for 20 years (removing price risk), priority access to the grid and compensation in case of curtailment due to grid stability issues (removing quantity risk)
- a mandate for system operators to balance forecast errors (removing imbalance risk)
- a preferential loan system to ensure access to financing, implemented by the German development bank via the retail banking sector
- training and certification programmes for installers.

Policy measures must help to ensure a smooth transition from the RD&D stages into the early stages of deployment. Significant challenges, mostly linked to a lack of co-ordinated policies to reduce investor risk and the resulting funding gap, can hamper the transition. The absence of adequate financing means that the point at which innovative energy technologies might be deployed in the market and prove themselves on a large scale may be delayed, or at worst fail, a phenomenon commonly termed the commercialisation "valley of death" (IEA, 2011a).

The policy approach for market inception also depends on whether a country aims to move a technology down its learning curve as part of deployment, or wants to benefit from past learning and deploy an already mature technology. In the latter case, the inception phase can be shortened significantly. Nevertheless, the market may need to be kick-started, keeping in mind that framework conditions need to be adjusted once deployment levels become substantial and the market enters the scale-up phase.

Scale-up phase

As larger deployment volumes are achieved, policy priorities need to be aligned with scale-up objectives, providing the right support structures that lead to deployment as effectively and efficiently as possible. A key learning from experience is that as deployment rates rise, overall policy support costs can escalate. The critical challenge, therefore, is to set deployment goals that keep costs within affordable limits for governments while providing sufficient incentives for investors. At the same time, it is critical to ensure that the policy environment can adjust to possibly rapid changes in market conditions. The evolution of solar PV deployment in Germany and Italy illustrates some of the challenges associated with faster-than-expected market growth for this particular technology (Box 4.3).

Box 4.3 Dealing with accelerated growth in the scale-up phase: Solar PV in Germany and Italy

One of the main challenges of a price-based instrument such as FITs or premiums is setting the right price, which, if done administratively, requires a well-informed decision by the responsible authority. Prices need to follow cost developments and thus have to be adjusted regularly. In the past, this has been more challenging for PV than for any other technology, as cost decreased unexpectedly quickly in recent years. Moreover, in the case of solar PV, the control of deployment volumes has also been challenging in the past. Germany and Italy provide interesting insights in this regard.

Italy offered very generous FITs to PV installations between 2005 and 2011. The original 2005 capacity target for PV of 100 megawatts (MW) was reached in merely nine days. The target was increased to 500 MW the following year and entirely removed for the second phase of the support scheme (secondo conto energia) starting in 2007. Downward adjustments to the tariff under the third phase (terzo conto energia) in 2010 did not significantly slow down the market. A tariff reform in mid-2011 (quarto conto energia) introduced lower support levels, subject to regular decreases over time and an annual cap to control support costs paid to renewable energy generators. The announced reform led to an unprecedented rush of investors to register their installations under the much more generous secondo conto energia, which, due to a legal loophole that was introduced by parliament (GSE, 2014), was still open until June 2011.

Installed capacities more than tripled in that year and reached about 13 gigawatts (GW) by the end of 2011. The targeted volume for 2020 had been 8 GW. Italian policy makers attempted to limit costs by implementing retroactive changes in 2012 and 2014, which have had negative impacts for the overall confidence of investors in the Italian PV market.

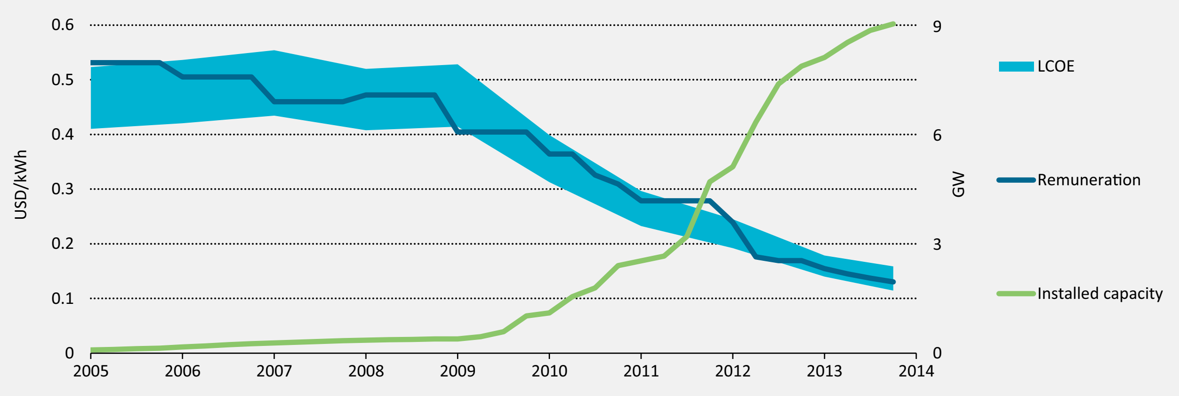
Germany, struggling to keep its PV support costs under control for some years, has introduced a number of innovations in its FIT policy over time to address this issue. Figure 4.3 shows how PV support levels gradually decreased over time, following decreases in the levelised cost of energy (LCOE). PV started to receive noteworthy support with the introduction of the Renewable Energy Act in 2000. As PV installation rates exceeded planned volumes, a support scheme reform in 2009 introduced the so-called "breathing cap", an adjustment mechanism for PV support levels. Downward tariff adjustments are linked to recent capacity additions: if actual installed capacities exceed a pre-defined target corridor, the tariff for new plants decreases faster in order to slow down deployment. If actual capacities are below the target corridor, the tariff decreases more slowly.

Policy portfolios at this stage should meet the following requirements.

- **Create a stable support environment, with credible and ambitious targets:** countries that have been successful in stimulating deployment at low cost always provide stable framework conditions that create investment certainty. A first and important step is to communicate policy objectives with clear, credible and quantitative targets.
- **Ensure flexibility of support mechanisms:** building regular reviews of support instruments into the policy package facilitates rapid adaptation to changing market conditions. Reactions can also be predetermined, for example by linking FIT levels to deployment volumes or quotas to certificate prices.
- **Develop transitional incentives, decreasing over time:** declining incentives are shown to stimulate further learning and lead to cost reductions. When setting support levels for renewable energy technologies, governments frequently announce a certain target range

for return rates on a project basis; typically internal rates of return are calculated at 7% to 12%. This approach can lead to over-subsidisation. Renewable energy technology assets tend to be priced based on the value provided for the project developer. An excessive tariff leads to higher system prices, as part of the excess profit is absorbed at higher levels of the value chain. If national system prices are assumed, this effect may not be identified clearly: benchmarking prices across countries is an important tool to avoid excessive tariffs.

Figure 4.3 Development of LCOE, remuneration levels and installed capacity for utility scale PV, Germany



Key point *Remuneration levels need to be adjusted frequently to keep track of falling costs to avoid very rapid deployment.*

- **Cap annual new financial commitments resulting from support:** for solar PV, keeping the level of support close to actual investment cost may not suffice to control the pace of deployment, and thus the total policy costs. Containing costs can be ensured by setting caps on the total amount of funds committed for support per year, at least for some segments of the solar PV market (large-scale systems).
- **Track global trends against national markets:** tariff changes in one market can influence the relative competitiveness of others, and thus the overall deployment dynamics. Tariff adjustments, for example, need to account for how global learning affects national system prices. When expanding renewable energy technology markets, countries need to act nationally but be aware of global trends.
- **Build on early mover experience, acknowledging the game is changing:** policy makers need to acknowledge the limitations of replicating approaches that were successful for early movers. While past success can provide valuable lessons for how to kick-start a mass renewable energy technology market, conditions change quickly today, and may create a need for shorter review cycles and quicker degression schedules.
- **Tackle non-economic barriers and implementation details:** if overlooked or ignored, these elements can undermine policy efficacy and cost-effectiveness. The PV boom in Spain, for example, spun out of control partially because the relevant law included a moderate capacity cap but tariffs were guaranteed for a year beyond the cap. During this period, the Spanish PV boom occurred (IEA, 2011a).

Past experiences (Box 4.3) highlight some of the challenges in policy design for inception and scale-up of solar PV. Despite some problems, it is clear that past support schemes have triggered tremendous cost reductions, which suggests that future deployment will come at significantly lower cost. While the strategies for these phases are increasingly well understood, to achieve the vision of the 2DS, more and more countries will need to move on to the mainstreaming phase for wind and solar PV.

Mainstreaming wind and solar PV into power systems

In the mainstreaming phase, the increased complexity and the required system focus means a change in priorities for renewable support policies and electricity market frameworks. As pointed out, some of the associated challenges in the mainstreaming phase are common to all low-carbon technologies. The most relevant ones are:

- pricing of externalities, in particular CO_2 emissions
- unlocking investments in capital-intensive technologies
- overcome existing lock-in of fossil fuel generation.

For wind and solar PV in particular, two additional aspects are of primary importance:

- ensuring operational efficiency at large shares of variable and distributed generation
- securing sufficient investments in flexible resources.

While many of the questions associated with mainstreaming wind and solar PV deployment are intimately linked to the general challenges of achieving the 2DS, this section will keep a more narrow focus on these issues from the perspective of wind and solar PV. The text acknowledges that some questions can be addressed only once deployment reaches levels at which these characteristics start to influence or interact with energy markets.

Pricing externalities: Limitations of carbon pricing

Carbon pricing is a critical, necessary element for a policy and market framework that stimulates decarbonisation in the energy sector. Basic economic theory suggests that putting an appropriate price on CO_2 emissions is sufficient to achieve decarbonisation at least cost. Several arguments raise diverse points about why determining and enforcing what is “appropriate” in practice is a substantial challenge, not only for wind and solar PV but for all low-carbon technologies.

The first point is the significant uncertainty regarding the actual cost of CO_2 emissions. The precise consequences of climate change and their associated costs are difficult to assess, making it impossible to accurately derive the “right” price or the “optimal” cap for CO_2 emissions. As this uncertainty cannot be removed, any price for carbon emissions will be derived rather pragmatically and can, in principle, always be challenged as being too high or too low. The same is true for a cap on emissions.

Ultimately, carbon pricing is a political construct – i.e. a government intervention designed to stimulate investment and innovation in a certain direction. As such, any investment exposed to a carbon price is exposed to a degree of regulatory risk; this can be mitigated, but never fully removed. This set-up has important implications on the investment risks associated with both high-carbon and low-carbon technologies: high-carbon prices or the expectation of high prices may deter investment in polluting options, but low-carbon prices or the risk of low prices may thwart investment in cleaner options. Moreover, an investment made under the assumption of a high-carbon price may become uneconomic if the government decides to remove the price.

Without a direct constraint on carbon, market participants are likely to continue to deploy energy options without any regard to their CO_2 emissions. Thus, pricing carbon is critical to advancing progress towards a fully decarbonised system. Over time the role of pricing carbon emissions to ensure revenue sufficiency for low-carbon options will decline. Once electricity demand is met using only low-carbon sources, a high CO_2 price will not drive market prices, because no CO_2 will be emitted.

Achieving near to full decarbonisation requires continued innovation in low-carbon power generation technologies. As shown by the recent cost reductions of solar PV, it must be acknowledged that the cost of different options to abate CO_2 is dynamic.

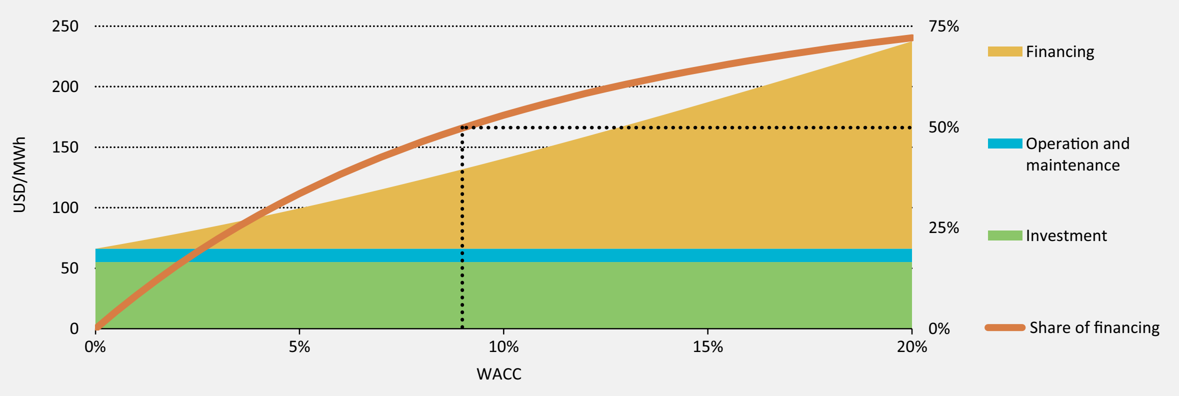
As the case of PV shows, such learning is unlikely to occur based on CO_2 pricing alone (IEA, 2011b). Unlocking innovation and learning by doing for low-carbon technologies is of paramount importance. If technologies are not brought to maturity in time, the cost of reaching more stringent CO_2 targets would rise sharply once inexpensive options are exhausted. The problems surrounding timely implementation of a carbon pricing mechanism and the challenges outlined above call for additional instruments to stimulate progress. Given the urgency of taking action against climate change, stakeholders are increasingly faced with the need to advance decarbonisation before a global price for carbon is in place.

Unlocking investments in capital-intensive technologies

Most low-carbon technologies in the power sector (including all renewables with the exception of bioenergy) incur the majority of their costs up-front. They are costly to build, but comparably inexpensive to operate. The opportunity cost of producing electricity from a PV system, for example, is almost zero.

Attracting investments in low-carbon technologies thus means mobilising large amounts of funds for up-front investments (IEA, 2014a). The weighted average cost of capital (WACC), which is a mix of the rate of return on capital and the interest rate for debt, at which the necessary capital and debt can be obtained is a crucial factor shaping the delivered cost of energy from low-carbon technologies. The lower the WACC, the less expensive low-carbon energy is. In turn, factors that increase the WACC drive up the cost of delivered electricity. In the case of solar PV, if the WACC exceeds 9%, financing costs begin to dominate the overall cost of solar PV electricity (Figure 4.4).

Figure 4.4 Impact of cost of capital on the levelised cost of solar PV



Key point *Financing costs can dominate all other components (equipment costs, O&M) of LCOE for solar PV.*

Several factors influence the cost of financing.[3] For technically mature technologies, the most relevant risks are those associated with the general investment climate in a market, the maturity of the local supply chain and the offtaker agreement (reflecting price, quantity and imbalance risks). Depending on the policy, market and regulatory framework, investors may be exposed to substantial risk, which is bound to increase the WACC.

In summary, delivering low-carbon investments at least cost means minimising risks for investors. Policy, regulatory and market frameworks can minimise risks for investors in two different ways: they may simply shift risks away from investors and onto someone else (usually electricity consumers or taxpayers), or they may reduce the risk *per se* or mitigate its impact by allocating risk to those actors that are best positioned to absorb it.

Policy and regulatory risk is a good example of a risk where governments have direct control over the magnitude of the risk. Where policy and regulations are adapted in a foreseeable and consistent way, the associated risk is low and so will be the cost of capital. Conversely, where government moves appear erratic, higher costs will be the result.

Overcome existing lock-in of fossil fuel generation

Power systems have evolved quite differently, depending on each country's resource endowment (availability of hydro power or domestic fossil fuels) and economic structure and political systems (planned versus market-based economy). Decarbonisation implies a radical departure from historical system development and investment patterns that have focused on carbon-intensive solutions and comparably lower levels of distributed generation. This further highlights that such a radical change across infrastructures and the surrounding industries will be feasible only with clear policy intervention.

Apart from getting low-carbon generation into power systems, an equally important challenge is removing high-carbon assets. As the modelling for the 2DS shows, significant fossil fuel capacities will need to be retired before the end of their technical lifetime if they cannot be retrofitted with CCS. A more detailed consideration of these aspects is beyond the scope of this chapter.

Ensuring operational efficiency at large shares of variable and distributed generation

For many low-carbon generation options, it is not possible to adjust electricity output in a fully flexible manner. Wind and solar PV are constrained by the real-time availability of the relevant resource. The variability and uncertainty inherent in wind and solar resources create new challenges for ensuring the quality of electricity generation. Previous analysis by the International Energy Agency (IEA) shows that power systems featuring a high share of variable generation can operate almost as cost-effectively (i.e. they carry little additional cost) compared with systems composed of dispatchable generation (IEA, 2014c). Achieving this cost-effective outcome, however, requires all of the system components (variable renewables, dispatchable plants, and transmission and distribution systems) to be integrated through a systems approach that also optimises short-term operations.

System operations routinely deal with the variability and uncertainty of demand. However, introducing variability on the generation side is a relatively new phenomenon for system operation. Existing experience of system operators in countries with a high-VRE penetration has shown how to adjust operations to this new situation.

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[3] See Chapter 8 in IEA (2014a) for a more detailed discussion.

Power systems can often supply a greater amount of flexibility than is demanded at moderate shares of wind and solar PV. However, the amount of this flexibility that is available at any given time depends on the way the system is operated. Given that wind and solar PV forecasts are more accurate closer to real time, power plant schedules should ideally have the option to be updated accordingly. Otherwise, a power plant that may be technically capable of supplying flexibility may be prevented from doing so due to a binding schedule that is based on outdated information. Similar considerations apply for the use of grid infrastructure, in particular interconnectors between different power systems (IEA, 2014b).

Demand-side integration and – where cost-effective – electricity storage will need to contribute to balancing supply and demand at high shares of wind and solar PV generation. Using these resources efficiently requires a holistic approach to operating the power system.

Finally, operating power systems at high shares of wind and solar PV generation also calls for the effective co-ordination of many power generation facilities. Deployment of wind power and solar PV frequently occurs at a scale that is much smaller than conventional power plants. As a result, a system relying heavily on wind and solar PV may have thousands or even millions (if rooftop PV systems are used) of individual generation facilities.

Policy, regulatory and market frameworks need to facilitate efficient operations under these changed circumstances and may thus need to be revised.

Securing sufficient investments in flexible resources

In most power systems, improved operations will not be sufficient to reach the high shares of wind and solar PV associated with the mainstreaming phase. Additional investments in flexible resources will also be necessary. Securing these investments becomes an important aspect of the overall policy, regulatory and market framework.

Sufficient flexibility can be delivered though an appropriate mix of the four power system resources: flexible generation, grid infrastructure, demand-side response and storage (IEA, 2014b).

The coupling of electricity and heat generation, via co-generation and thermal energy storage, can make a critical contribution for mitigating both structural wind and solar PV generation surpluses and shortfalls – if the operation of these assets is well managed. During surplus situations, electricity can also be used for heat generation. When thermal storage is installed, surplus electricity can be used to cover heat demand several hours later. In addition, such a configuration allows co-generation plants to cover situations of electricity scarcity. Where there is a significant demand for cooling (air conditioning) the same principle can be applied using cold storage. Similarly, charging of electric vehicles may be geared towards times when wind and solar PV are available (IEA, 2014b).

As long as there is uncertainty about future development paths, investors will face a conundrum: many integration options to increase flexibility will be economically viable only if VRE is deployed at a large enough scale to create sufficient demand for flexibility. In turn, the market value of VREs will remain robust (even as penetration increases) only if investments in flexibility go ahead at scale. As such, this area requires due consideration in the mainstreaming phase.

Meeting the mainstreaming challenge in different system contexts

As seen from their respective characteristics, stable and dynamic systems are in quite different starting positions in terms of large-scale wind and solar PV deployment as part of their decarbonisation strategy. This is linked in part to the different general investment climate in these systems but also related to differences in the current policy, regulatory and market frameworks in place.

Liberalised markets in stable systems have demonstrated their ability to greatly improve operational efficiency: the largest liberalised power market in the United States achieved annual savings of approximately USD 2.2 billion (PJM, 2014). By contrast, the highly regulated nature of vertically integrated markets provides security to attract investment, which is a frequent struggle in liberalised markets.

Indeed, 90% of all power sector investments between the early 2000s and 2014 took place in heavily regulated environments. Part of these investments took place in dynamic systems without liberalised markets. Another part was due to out-of-market investments in systems that have liberalised markets in principle, e.g. renewable energy investments in Europe (IEA, 2014d).

Ultimately, an integrated policy, regulatory and market framework for reaching the 2DS may require a degree of convergence across the two systems. Where market liberalisation has taken place, there is likely to be a need for policy instruments that increase investment certainty in low-carbon technologies; in regulated markets, there is a need to ensure transparent and fair grid access rules for low-carbon generation as well as measures to maintain or improve operational efficiency.

The remainder of the chapter analyses how to address the challenges of the mainstreaming phase depending on system context. In order to simplify the discussion, the focus will be on two broad contexts: stable systems with liberalised markets and dynamic systems with regulated electricity systems.

Regulated context: Improving transparency and operational efficiency, maximising investment certainty

The regulated environment for investments in generation capacity, combined with the need for investments in dynamic systems, can be conducive to the update of capital-intensive low-carbon generation including wind and solar PV. This could be an advantage in general. However, there are numerous factors that may challenge investment certainty in dynamic systems.

Experience shows that possible adverse impacts of adding VRE to power systems tend to be overestimated at the onset of deployment. Usually, the anticipated effects are linked with concerns to the overall system operability (IEA, 2014b). Economic issues and institutional inertia may pose barriers to mainstreaming wind and solar PV into regulated contexts, including dynamic power systems with high need of power sector investments. Incumbents may feel threatened by new generation, as it introduces competition with other investment options that incumbents are in a better position to invest in. Moreover, regulatory incentives for renewables may fail to capture some of the benefits renewable energy brings. Where fuel procurement is a significant risk, for example, the value of wind and solar PV in decreasing required fuel volumes may be relevant yet not reflected in the economic incentives for utilities (e.g. the risk of fuel supply disruptions may not be priced). In other cases, generators may receive fossil fuels at subsidised prices, creating an inefficient bias towards fossil generation.

Transparency and operational efficiency

Where market liberalisation has not taken place, system operation and ownership of existing generation plants tend to coincide and the operation schedules of power plants can be strongly influenced by long-term supply contracts. These conditions can result in significant conflict of interest and lead to a situation in which adding wind and solar PV to the system may compromise the economic value of existing assets.

When power plants that incur costs for fuel displace generation from wind and solar PV, the actual cost is higher than needed. This is the case in China, where long-term agreements determine which plants will operate and less costly wind generation is curtailed to “make room” for coal-fired power plants. Similarly, wind generation in India may be curtailed in favour of burning fossil fuels, if the price for electricity procured by unscheduled interchange drops below the preferential rate paid to wind power generators.

Dynamic systems often lack a characteristic that has come to be critically important in mainstreaming wind and solar PV in stable, liberalised markets: transparent procedures for assessing the technical feasibility of integrating growing shares of renewables into the power system. Where decisions on grid integration are made by an entity that also owns generation assets, or is closely linked to owners of generation, conflict of interest may arise. Establishing a mechanism that ensures impartial assessment of the technical issues surrounding grid integration may be a key step towards improving transparency and gaining investor confidence.

Co-ordinating system operation across multiple service areas of vertically integrated companies is also challenging. Indeed, one of the most important drivers behind market liberalisation has been ensuring more efficient operation across larger geographic areas; with growing penetration of wind and solar PV the possible benefits of harmonised operation are increased (IEA, 2013a). In regulated markets, supplementary mechanisms for ensuring efficient operation across larger geographic areas will likely be a priority. Japan, for example, is currently discussing the establishment of a co-ordination body to manage exchanges (Organization for Cross-regional Coordination of Transmission Operators [OCCTO]) among the nine mutually connected utility service areas (METI, 2014).

For capacities in a regulated environment that are procured under long-term PPAs, introducing location-based and time-of-generation provisions may help to provide necessary price signals. A wind or solar PV power plant that produces close to load centres and with output that correlates fairly well with times of peak demand, for example, should receive a higher remuneration than a distant plant that generates during off-peak times.

South Africa recently introduced a multiplier in solar thermal power auctions open to IPPs. During daylight hours, IPPs will receive a base price; during peak hours in late afternoon and early evenings, this base price will be multiplied by 2.7 to reflect the cost difference between base load and peak load electricity generation in South Africa (South Africa Department of Energy, 2014).

Such price differentiation can signal the time- and location-specific value of electricity generation. In a regulated environment, this requires an informed entity to make projections about future demand patterns and the evolution of the overall generation portfolio. Such planning approaches also need to accurately factor in the potential contribution from the full spectrum of possible flexibility options (flexible generation, grid infrastructure, demand-side response and storage).

Putting in place mechanisms that allow for efficient system operation and planning may help to eliminate economic conflict. The possible design of such planning and regulatory instruments in dynamic systems is central to ongoing analysis as part of the IEA Grid Integration of Variable Renewables (GIVAR) programme but beyond the scope of this chapter.

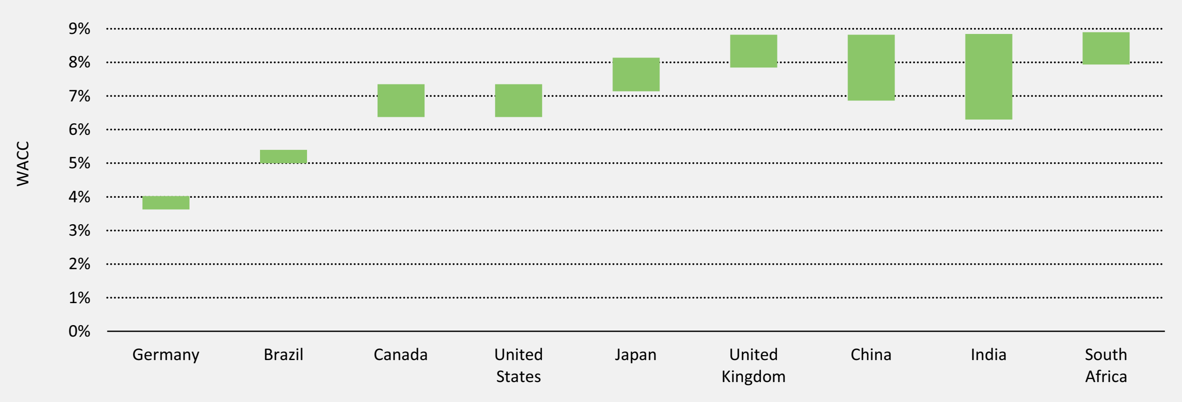
Ensuring investment certainty

Investments in the highly regulated environment of dynamic systems are typically made either directly by fully vertically integrated companies or indirectly by IPPs under a long-term PPA with a regulated entity. Given the long-term nature of such contracts, the price and quantity elements that create risk in liberalised markets (as discussed below) are of minor importance.

Where growing demand creates a need for new investments in dynamic markets, the regulated environment could be conducive to favouring capital-intensive low-carbon generation including wind and solar PV.

However, efforts for minimising the cost of capital are a critical element for streamlining low-carbon generation – including wind and solar PV – into dynamic power systems with a more regulated context. Comparing the estimated WACC across different jurisdictions highlights the wide spread across countries and sometimes higher levels in dynamic markets (Figure 4.5).

Figure 4.5 Onshore wind real WACC, 2013



Key point *WACC shows significant, country-specific differences, reflecting different levels of risk for investors.*

This elevated cost of capital in dynamic systems (as compared with stable systems) also reflects additional risks that may be associated with investments in these countries such as perceived political risk and volatile currency exchange rates. While the policy, market and regulatory framework in dynamic systems may be conducive for low-carbon investments, broader risk categories may pose a larger challenge. Ensuring access to appropriate financing resources in combination with awarding long-term PPAs is a priority to secure investments in dynamic systems. Existing country experience shows how this can be achieved in practice. For example, the Brazilian auction system combines long-term investment security via a PPA with a long-term loan at preferential rates from the Brazilian development bank.

Liberalised context: Reconciling liberalised markets with investment certainty

In many leading countries for wind and solar PV deployment, electricity market liberalisation has been instrumental in bringing deployment to scale.

Fostering competition in generation and increasing efficiency via trade across large geographic areas are key objectives of market liberalisation, and have been achieved, at least in part, by separating ownership of generation from operation of the transmission system. This creates fewer barriers and more transparent processes for obtaining relevant permits to build new generation plants and greatly facilitates grid access for generators, including renewables. In addition, wind and solar PV are characterised by low short-run costs: once the plants are built, their fuel is free. Thus, in liberalised markets, they are very likely to be at the bottom of the merit order, and called upon first in the spot market to meet electricity demand at a given point in time.

Increased emphasis on larger trade areas (geographical aggregation, also a principal driver for market liberalisation) can help "smooth out" the variable nature of wind and solar generation. This reduces overall operational costs compared with a scenario in which supply and demand are balanced across smaller areas.

However, a number of specific challenges need to be overcome to maintain operational efficiency and reconcile liberalised markets with the investment certainty needed for mainstreaming wind and solar PV.

Ensuring operational efficiency and sufficient levels of power system flexibility

In order to efficiently co-ordinate system operations, electricity markets need to adequately price both the electricity generated and the system services that underpin generation, transmission and distribution. As market liberalisation was initiated before wind and solar energy showed signs of becoming serious contributors in power generation (and without consideration for how they would influence operations), certain elements of the pricing mechanisms designed for existing systems need to be improved.

High shares of wind and solar significantly alter the technical capabilities that the power system needs to deliver during operations. The first related challenge is to secure adequate levels of capacity and operating reserves during periods when electricity demand approaches available generation capacity (scarcity periods). In addition, high shares of wind and solar PV may boost the value of other capabilities, including fast ramping, low turndown, fast starting and inertial response.

The design of liberalised electricity markets needs to be reformed to reflect these new operational realities, so that price signals capture times when certain system capabilities become scarce and warrant a high price. Trading closer to real time and at short intervals are already proven mechanisms to appropriately remunerate a number of these capabilities (IEA, 2014b).

Establishing dedicated system service markets can help to support appropriate remuneration of system critical services, often by facilitating simultaneous trading on wholesale markets so that prices on one market drive prices on the other, thereby better reflecting actual value. This approach is currently being considered in several European electricity markets including Germany, Ireland and the United Kingdom.

An alternative approach – known as co-optimisation – is to consider the value of system resources when clearing the wholesale power market close to real time. Simply put, this means that power plants that provide valuable services to the system are more likely to be called upon and/or receive payments above and beyond the price of wholesale power. Remuneration of flexibility is built into the regular wholesale market. This approach is implemented or under discussion in several US markets (NREL, 2014).

Ultimately, which capabilities become particularly relevant (and therefore highly valued) for decarbonisation at high shares of variable generation will likely be system-specific. Governments would do well to apply available modelling tools to guide market design and inform decisions on necessary capabilities and price signals. Ireland is currently implementing a creative market design for system services based on the results from using a comprehensive set of power system models to identify the relevant products (EirGrid and SONI, 2010).

These incremental improvements to existing, liberalised market designs are the subject of ongoing IEA work and will feature prominently in the upcoming publication *Electricity Market Design for Low-Carbon Energy Systems* (IEA, forthcoming). The principal change from such improvements will be a more appropriate remuneration of the provision of flexibility and firm capacity to meet peak load. In addition, the participation of demand-side response and storage would become more likely to grow closer to their actual potential.

However, a number of issues would almost certainly remain unresolved from such incremental improvements.

Transitional overcapacity and merit order effect

Decarbonising grid-based electricity is about changing how an existing service is provided, not providing a new service. From an end-user perspective, electricity is electricity: “high-carbon” and “low-carbon” are perfect substitutes for each other and, climate implications aside, deliver exactly the same product. In fact, decarbonisation could be viewed as something that offers consumers the same service,[4] with the uncertain advantage that they may be helping to avoid the somewhat abstract and still distant threat of climate change.

The relevant point for generators is that both types of electricity compete in the same market. This becomes a challenge, if the speed at which low-carbon generation is added outpaces the need for new investments to meet growing demand or replace ageing infrastructure, and accounts for the economic challenges observed in markets where incentives have prompted rapid growth of wind and solar PV even though demand growth is sluggish.

For liberalised markets that operate on the merit order system, rapid introduction of low-carbon options can have serious impacts on incumbent assets. Merit order ensures that electricity demand is first met with low-cost generation; high-cost generation is called upon only if increased demand warrants the extra cost. Once built, low-carbon technologies provide low-cost generation. In fact, many have virtually no fuel cost and thus consistently take first place in the merit order. Combined with the overcapacity factors, the result is that incumbent assets with comparably high fuel costs are seeing dramatic reductions in their operating hours compared to what they might have anticipated in a situation with higher demand growth and less low-carbon generation.

Moreover, because low-cost capacity is used first, the price on short-term wholesale markets declines and all capacities earn less revenue for the hours they do operate. In effect, overcapacity also mutes scarcity prices on the wholesale market. Ultimately, this situation diminishes the value of both existing assets and new generation, creating a generally bad climate for investment.

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[4] Rooftop solar PV is a notable exception. Self-generated electricity may have a distinct value to consumers. This may alter market dynamics for this segment.

While some argue that slowing or stopping the addition of low-carbon generation is one way to halt this trend, such action may not be in line with reaching the 2DS target. The real challenge, then, is to create a market framework that supports continued investment in low-carbon generation while also ensuring an organised market exit of high-carbon capacity (thereby reducing the adverse impacts of stranded assets).

Cost structure and financing risk

Uncertainty about fossil fuel and carbon prices currently create risks that are a deterrent to low-carbon investment. In existing liberalised electricity markets (as explained above), system operators will tend to first call on generators with low short-run costs to meet demand. But in fact, it will often be other technologies – with higher short-run costs – that are setting the price on the margin. For example, this is the case for CCS technologies, which incur fuel costs. It can also be the case for fossil fuel power plants, still present in the system.

Fuel and (when present) emission costs determine the short-run cost of these price-setting technologies. When costs are high, low-carbon generators will benefit from high prices. But when prices decline, both high- and low-carbon generators will be exposed to low prices. The reason behind it is that, apart from their value of generating electricity, the benefits of low-carbon generation are saving fossil fuel (with the exception of CCS) and the avoided CO_2 emissions. As such, market revenues for low-carbon generation will fall when the costs of fuel and emissions are low.

In turn, when demand can be met solely from supply with almost zero marginal cost, short-term prices can be expected to plunge to almost zero. This can create a large gap between the average long-run cost (i.e. the levelised cost of electricity or LCOE) on which investment decisions were made and the short-run cost that determines actual revenues, introducing an additional source of risk for low-carbon technologies (Figure 4.6). At very high shares of low-carbon generation, prices may be very low for extended periods of time. The variability of wind and solar PV generation adds to this problem, depending on overall system flexibility.

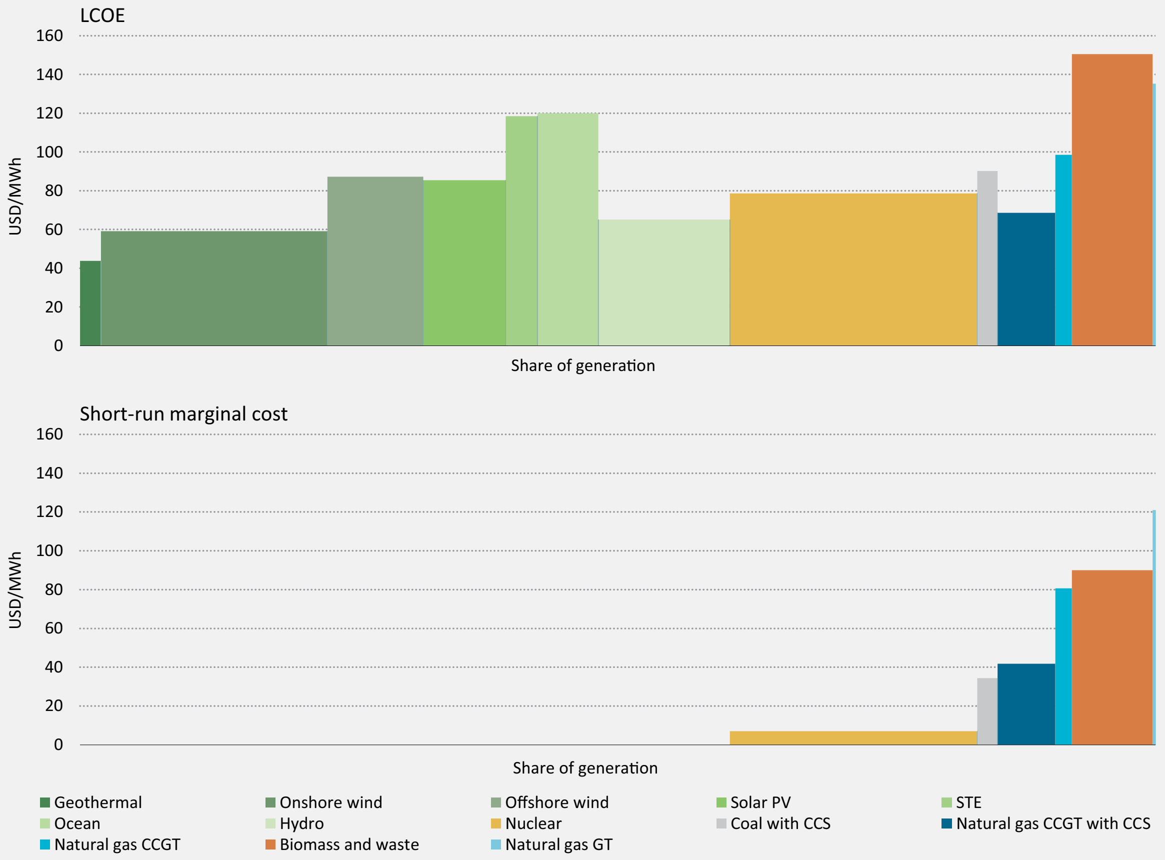
Such risks can make it very difficult to pay back the initial investment solely with revenues derived from short-term markets. In fact, it would require prices to surge during some hours of the year, when electricity demand is very high or supply constrained.

To attract financing, market participants need to have confidence that low-carbon generators will receive sufficient revenues to cover the large, up-front capital costs. Price uncertainty and risk have the compound effect of driving up the cost of capital, which pushes up the cost of low-carbon projects and increases the required revenues to deliver a satisfactory return.

In summary, it seems unlikely that the current model of liberalised markets plus a carbon price will deliver investments at a scale and pace needed to achieve the 2DS target. Rather, at minimum, markets should be reformed to include both a carbon price and well-designed, short-term markets. But even this combination may not suffice: additional instruments to secure investments and overcome the practical problems of decarbonisation are needed.

As renewable energy technologies are mainstreamed on the way to decarbonisation, rather than covering a cost gap in relation to fossil sources, the role of policies is shifting towards providing revenue certainty to mitigate risk for capital-intensive technologies. In the absence of such measures, the risks are likely to drive up the cost of deployment or hinder it altogether.

Figure 4.6 European Union long-run levelised costs and short-run marginal costs in the 2DS, 2050



Key point

In a low-carbon electricity system, a large gap between short-run and average costs can undermine the calculations on which investment decisions were made.

Given this conclusion, what options are available to increase investment certainty for low-carbon generation while continuing to reap the operational efficiency benefits of the liberalised model?

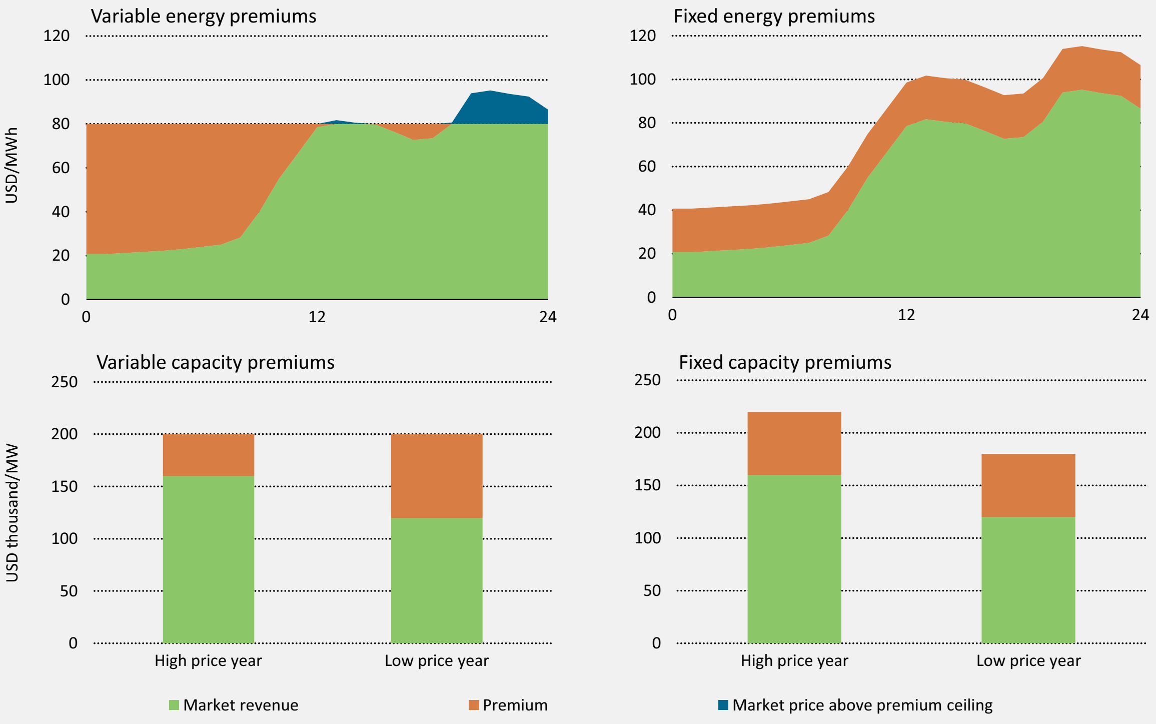
Instruments for improving investment certainty in liberalised markets

The uncertainties described above and associated risks are the principal deterrents to purely market-based investments in low-carbon generation. The challenge is thus to strike a balance between the level of higher market risk generators are willing to be exposed to and enough certainty to keep financing costs low. To achieve this, policies should interface with markets in ways that do not lead to undesired distortions.

One way to strike this balance is to establish market premium mechanisms that expose generators to some – but not all – price signals coming from wholesale power markets.

By definition, a premium aims to supplement market revenues to compensate for the gap between required revenues and actual market revenues. Depending on the type of premium used, different risks can be passed on to investors. Premiums can be paid per unit of energy (MWh) or per unit of installed capacity (MW). They can be fixed to a certain amount (fixed premiums) or calculated factoring in market price developments (variable premiums). Policy options to mitigate risk for generators are mapped in Figure 4.7 and explained further in the following text.

Figure 4.7 The influence of policy instruments on generator remuneration



Key point *By designing appropriate instruments, policy makers can adjust risk exposure of generators.*

Balancing risk

Establishing a market premium system through which generators can sell their electricity directly on the market, and thus shoulder the balancing risk, can be a first move towards increased market integration. Germany introduced a policy framework (in 2012) under which renewable energy generators are responsible for selling their power on the market, but they obtain a premium for each MWh of generation sold. The premium level is calculated such that the average generator of the particular technology (e.g. wind) would receive a payment (market revenue plus market premium) that matches the FIT (Figure 4.6, top left). The policy also includes a fixed per-MWh payment (management premium) to cover some of the balancing risk.

A subtlety about the German system should be noted. For a given technology, if a generator is able to produce an output of higher value (market prices) than the average, it is possible to make an extra profit, because the per-MWh premium level is calculated for the average generator. This induces competition within each generator category to secure sites and build power plants that will generate when prices are particularly high, i.e. generate electricity when it is most valuable.

Market risk (price and quantity)

The long-term prices on the electricity market are the biggest source of risk for investors. The degree to which low prices are passed on to investors thus directly influences the risk levels they need to bear. Two different types of premiums show a crucial difference in this regard. If the premium level is the same for different market prices (fixed or determined *ex ante*), this means that the total revenue that investors receive will depend on the market price. If the premium level is calculated such that market revenue plus premium meets a predetermined level (variable or *ex post* premium), lower-than-expected market prices will not be passed on to investors. In short: fixed premiums pass on market price risk to investors, while variable premiums do not, because the premium will increase to compensate for dropping market revenue.

The different premium systems also have an impact on quantity risk for investors. In general, quantity risk for wind and solar PV is fairly small, because they have low short-run costs and are thus the first to be called upon to generate. Nevertheless, at high shares of wind and solar PV there can be situations where generation does exceed demand. This can be the result of various factors, such as a minimum generation requirement for conventional power plants (IEA, 2014b). At this point, market prices can be very low or may become negative. The bidding behaviour of generators receiving a premium may lead to inefficiencies depending on the design of the policy instrument. If the premium is paid per megawatt hour, generators will have an incentive to bid below their actual cost in order to secure the premium payment. Where premiums are paid per capacity, such an incentive does not exist.

Energy-based instruments can include provisions that preclude such negative bidding practices. From an investor perspective, the risk of curtailment is reduced if there is an energy premium that is paid even during negative prices. If the premium is paid per unit of capacity or withheld during times of negative prices, investors are exposed to curtailment and thus quantity risk. Curtailment risk can halt progress for wind and solar PV deployment, as illustrated by developments in Ireland, where uncertainty about future curtailment practices halted deployment progress.

The economic relevance of bidding below short-run cost from wind and solar PV should be assessed to balance the increased uncertainty put on investors and its possible implications for the cost of financing. Empirical evidence from the German market indicates that negative price events remain rare at a combined share of roughly 15% wind and solar PV, with 64 hours of negative prices per year in 2013 and 2014, i.e. 0.7% of the hours. Most of German solar PV generation is supported by FITs while the majority of wind generation receives a market premium. Moreover, negative price events in the past have been instrumental in inducing learning effects for a more flexible operation of thermal plants (Nicolosi, 2012).

Determining premium levels

The way in which levels are determined will influence the effectiveness of premium schemes. Applying a competitive bidding process would allow for more accurate price discovery, but in case of variable premiums (per MW or MWh), the levels need to be calculated against a certain strike price. Problems may arise if this strike price is determined without factoring in the market prices different technologies will achieve. For example, solar PV may be more valuable than wind generation in a system with peak demand during sunny summer days.

Setting the strike price for a variable premium via an auction process will incentivise the lowest cost of energy generation, but because bidders will not take into account the electricity market value of the generation, the auction may not contract the technology that needs the least support. As such, auctions would not reflect well the value of the produced energy. Auctions for variable premiums may prove a viable mechanism, but would need a technology-specific design to overcome this issue.

The above example of solar PV in a summer peaking system illustrates this effect. Assuming that solar PV receives an average market remuneration of USD 80/MWh while it comes at a cost of USD 100/MWh, it would require a strike price of USD 100/MWh and a premium of USD 20/MWh. Assuming that land-based wind generation receives USD 60/MWh from the market and costs USD 85/MWh, it would require a strike price of USD 85/MWh and a premium of USD 25/MWh. So while wind is lower cost than solar PV, it requires a higher premium to cover the gap between costs and market revenues. These considerations are particularly relevant because the market value of wind and solar PV generation is very system-specific and drops with increasing penetration (Hirth, 2013; Mills and Wiser, 2012; NEA, 2012; IEA, 2014b).

The above example shows that variable premium systems are not inherently technology-neutral. Fixed premium systems, in which total remuneration is determined factoring in market revenues, are easier to implement in a technology-neutral way. However, as the discussion on market price risk highlighted, they put a considerably higher level of risk on generators.

Conclusions on different premium types

The discussion of different premium mechanisms has shown that by choosing different types of premiums (fixed versus variable) different levels of risk can be passed on to investors. Moving from a variable to a fixed premium system increases the risk for investors, because long-term movements in electricity prices are passed on to investors. Withholding premiums during times of negative prices allows avoiding potentially inefficient operating decisions, but achievable efficiency gains in operations should be weighed against the increased risk put on generators and the associated increase in financing cost.

In an environment characterised by a high degree of uncertainty about future electricity prices (e.g. depressed prices due to transitional overcapacity, uncertainty around CO_2 pricing, lack of clarity about how to achieve system flexibility), transferring all associated risks to wind and solar PV generators – and low-carbon generation more broadly – may inhibit investment or lead to very high costs to unlock investment. Until and unless the outlook for purely market-based revenues becomes more certain, supplementary mechanisms such as market premium systems are an appropriate intermediate step to compensate for transitory risk factors and successfully move wind and solar PV into the mainstreaming phase.

Recommended actions for the near term

Achieving the 2DS deployment levels for low-carbon energy technologies requires a step change over the coming decades in the policy, regulatory and market frameworks that underpin their deployment. As shown, the priorities for wind and solar PV deployment have shifted away from providing support primarily to achieve technology maturity. The current focus is on establishing market frameworks that deliver the revenue security needed to encourage these low-carbon investments in electricity systems that are exposed to a multitude of risks.

This advancement to mainstreaming wind and solar PV can be seen as the natural progression from the inception and scale-up phases, and indeed should draw on the wealth of experience gained as various countries have moved through these earlier stages. It is clear that the main challenges to deployment – and thus the requirements that framework conditions need to meet – change as technologies progress along this deployment curve.

Ensuring electricity system operational efficiency at large shares of variable and distributed generation is a priority in the mainstreaming phase. This calls for upgrading market rules and system operation protocols with a view to shift operational decisions closer to real time and ensure a level playing field for demand-side integration and storage to balance supply and demand. Mechanisms that optimise least-cost operation across large geographic areas are particularly relevant, as they can safeguard against increases in system costs.

The changing priorities and increased complexity of the mainstreaming phase for renewables requires a system approach, with a strong focus on securing investments in low-carbon electricity generation while maintaining sufficient assets to ensure system flexibility. Ongoing efforts to establish mechanisms to constrain carbon emissions and to achieve agreement on a global price on carbon will help to unlock investments in low-carbon technologies such as wind and PV. But these actions will not be sufficient, especially in the near term. Additionally, securing sufficient investments to support the needed innovation in flexible resources (particularly for demand-side response and cost-effective energy storage) calls for providing certainty about the future build-out path of wind and solar PV generation.

The two very different market contexts described are clearly in different positions for mainstreaming wind and solar PV, and will require different policy, regulatory and market frameworks to reflect diverse opportunities and challenges. Each will need dedicated instruments to attract sufficient investments in wind and solar PV (and low-carbon generation in general) by reducing the risk exposure of investors. In liberalised markets, market premium models can be an appropriate tool to facilitate investments while minimising market distortions. In regulated markets, priority needs to be given to providing clear and transparent access rules for new generation, and designing long-term PPAs that reflect the value of assets from a system perspective.

Overcoming the existing lock-in of fossil fuel generation is equally important, particularly in stable power systems. Governments have a role in providing clear and consistent exit signals to ensure an organised move away from high-carbon options while minimising the costs associated with stranded assets.

Early efforts to mainstream wind and solar PV suggest that achieving the 2DS – and ultimately deep decarbonisation of the energy system – will require significant changes to policy, market and regulatory frameworks and may imply a degree of convergence between characteristics of liberalised and regulated markets. Further research is needed to derive stronger conclusions.

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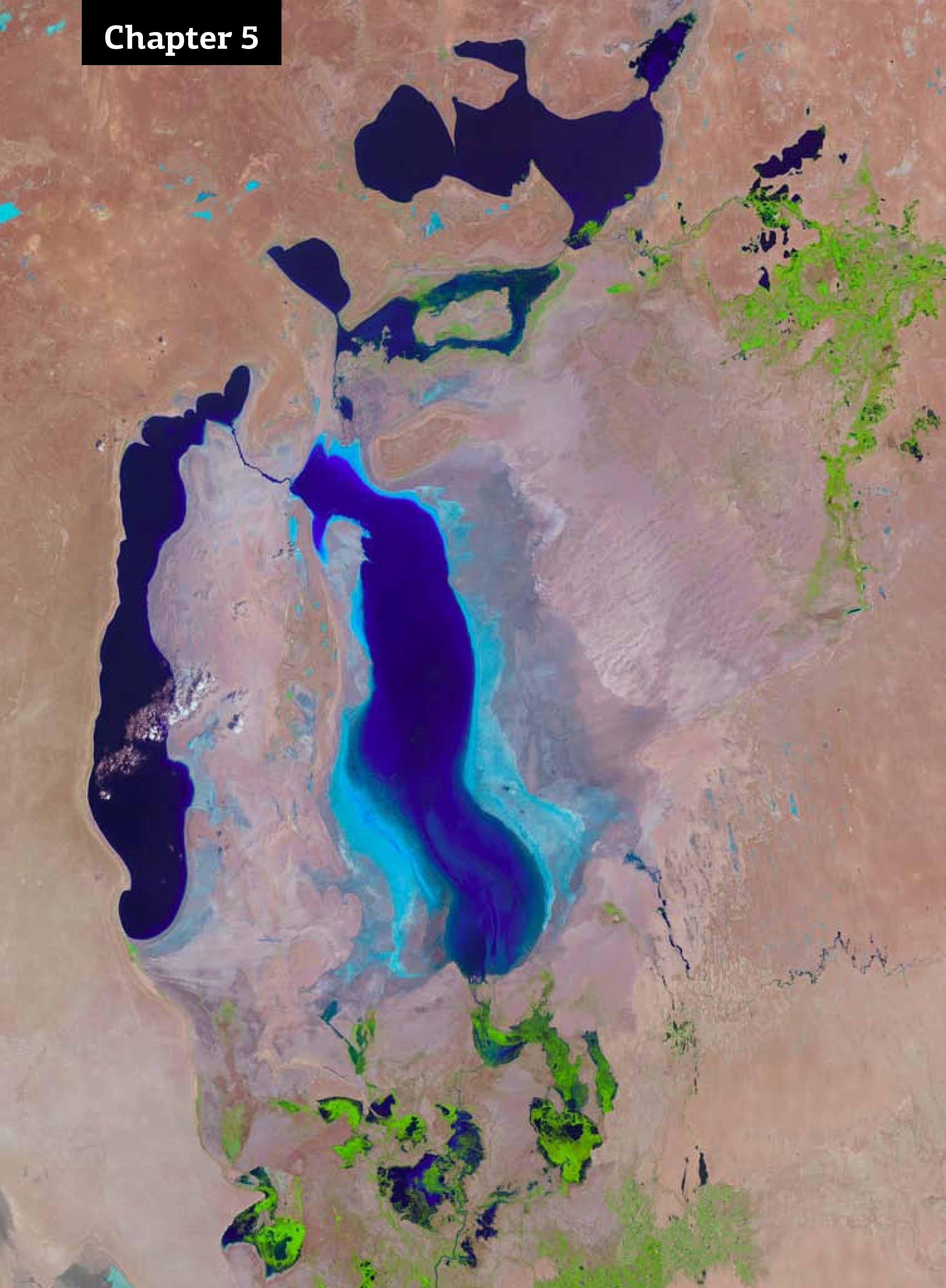
Chapter 5



CCS: Building on Early Opportunities

Carbon capture and storage (CCS) remains a vital technology to meet long-term global climate goals for emissions reduction. CCS is already commercially used in certain regions and sectors where industrial, social and political factors align. To reduce the cost gap and stimulate innovation, increased policy action is needed to create more market opportunities in parallel with continued research and development (R&D).

Key findings

- ***In the 2°C Scenario (2DS), almost 6 billion tonnes of carbon dioxide (CO_2) per year are captured and stored by 2050 in all sectors.*** *CCS in industrial applications is essential, and CCS in combination with biomass may be needed to meet the 2°C target.*
- ***CCS deployment has begun in "sweet spots" where policies and strategic local and commercial interests align****. Many opportunities for CCS technologies have been in natural gas processing or hydrogen production, often in combination with enhanced oil recovery (EOR). EOR has supported early commercial projects, but other policy drivers have been equally important in making them happen.*
- ***"Learning-by-doing" is now also under way for CCS in power generation.*** *The world's first power plant to be equipped with CCS technologies began operation in 2014. As with other such sweet spots, appropriate market structures, opportunities for the continued use of low-cost fossil fuel reserves, government support and confidence in the future of the technologies were all vital.*
- ***Widespread deployment requires the cost gap be closed by determined, parallel action in technology development and market creation.*** *R&D alone will not deliver the necessary performance improvements and cost reductions. Innovation will also arise from commercial experience in relevant sectors and measures that raise the costs and risks of operating without CCS.*
- ***Improving and using post-combustion technologies is of particular importance.*** *Reliance on coal, especially local resources, could continue in many regions, as coal prices decline in the 2DS. One-third of today's coal power plants were commissioned since 2000 and will have many years of useful life after 2030, indicating the value of technologies enabling CCS retrofits. Technologies to integrate CCS in new electricity generation cycles also need to be developed.*
- ***Innovation and robust regulation will help CO_2 storage remain a minor cost component of CCS.*** *By providing incentives for exploration and clear, credible regulation, governments can boost engagement of the oil and gas sector and create vital public support. Large-scale CO_2 storage projects are needed to support innovation in finding, developing and monitoring storage sites.*

Opportunities for policy action

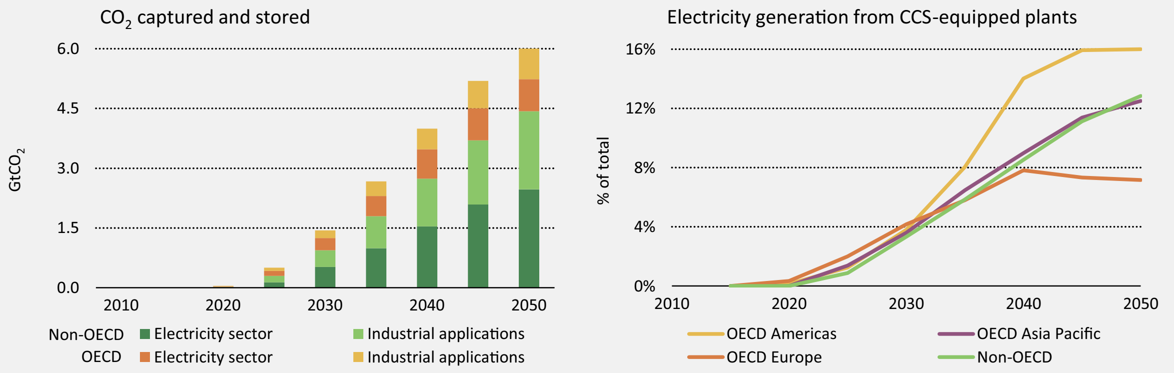
- *Strategically aligned action across three areas can reduce investment hurdles and project risks, thereby stimulating new commercial opportunities. Governments should actively support: learning-by-doing in commercial-scale projects, to optimise opportunities in sweet spots; learning-by-researching to generate new technologies and methods in research labs and networks; and the use of policy measures (e.g. ambitious climate policy, regulations, tax incentives) to stimulate innovation, create new sweet spots and strengthen existing markets.*
- *Near-term efforts should focus on developing markets for CCS in sectors and regions where the technology and mitigation costs can be most easily borne. This includes sectors where* CO_2 *capture costs are low and where other commercial and strategic conditions already exist. EOR opportunities can be leveraged in this context, but maximising their* CO_2 *abatement requires a supportive regulatory environment.*
- *Public R&D investment could play a lead role in the development of new approaches to* CO_2 *capture for power plants, including better post-combustion capture and advanced generation cycles. Lower costs and improved performance in these areas are vital to realising the technology learning rates in the 2DS. Allocation of R&D resources should consider how new technologies might affect capital costs and raise flexibility and efficiency, noting that future electricity markets may change the values of these factors.*
- *Technical and regulatory innovation together will be needed to reduce up-front risk and keep storage costs low as a proportion of total CCS costs. An important element of this is reducing the costs of exploring and developing* CO_2 *storage sites. Policies that manage competition for skills and resources between* CO_2 *storage and the oil and gas sector may also be important.*
- *Portfolio approaches to technology support, coupled with knowledge sharing, can accelerate innovation across a diverse set of technology options. It is currently unclear which* CO_2 *capture technologies will be most effective in delivering cost reduction and performance improvements. Balanced portfolios include technologies representing both lower-risk, incremental improvements and higher-risk, more radical improvements. In the longer term, necessary cost reductions may be achievable only with technologies that fully integrate CCS in production processes.*
- *Instruments being developed within the United Nations Framework Convention on Climate Change (UNFCCC) provide opportunities to accelerate policy action this year. Because CCS is a technology of global importance, with high project development costs for individual countries, UNFCCC backing could make a major contribution. New markets and more experience could be fostered by enabling countries to support CCS projects through the Technology Mechanism, Green Climate Fund, Nationally Appropriate Mitigation Actions and others.*

Unless CCS becomes a viable carbon-mitigation option, there is a risk that energy system CO_2 emissions will not be reduced to levels that limit global warming to 2°C (Bruckner et al., 2014; Krey et al., 2014). The importance of CCS is seen clearly in the 2DS, in which 43% of primary energy in 2050 is still being supplied by fossil fuels, including natural gas and coal.

CO_2 emissions from natural gas have increased by nearly one-third in the last ten years, while coal has been the fastest-growing source of primary energy for the past five years in absolute terms. More than one-quarter of Chinese coal demand is for steel and cement production (IEA, 2014a). In these and other important production processes, including processes in the chemicals and refining sectors, CCS is recognised as the only available way to reduce emissions intensity by over 50%. At the same time, many studies indicate that a 2°C pathway will require the combination of CCS with biomass energy, or even CO_2 capture from the air,[1] by mid-century (Bruckner et al., 2014).

CCS involves integration of three processes: separation of CO_2 from mixtures of gases such as flue gas and compression of this CO_2 to a liquid-like state (CO_2 capture); transport of the CO_2 to a suitable storage site (CO_2 transport); and injection of the CO_2 into a geological formation where it is retained by a natural (or engineered) trapping mechanism and its behaviour monitored to ensure permanence (CO_2 storage). In the 2DS, CCS deployment increases markedly from 2030, with CO_2 captured and stored in industrial applications as well as the electricity sector where 16% of electricity generation in the Americas region of the Organisation for Economic Co-operation and Development (OECD) is equipped with CCS by 2045 (Figure 5.1). In OECD non-member economies the share of CCS also exceeds 10%, and over two-thirds of total CO_2 captured and stored is in OECD non-member economies.

Figure 5.1 CCS deployment in the 2DS



Notes: $GtCO_2/yr$ = billion tonnes of CO_2 per year. Figures and data that appear in this report can be downloaded from www.iea.org/etp2015.

Key point *CCS deployment takes off after 2025 in electricity and industrial applications. Over two-thirds of total CO_2 captured and stored is in OECD non-member economies.*

Although CCS is expected to play a major role, it faces many barriers. While many experts view CCS as an effective technological solution to the problem of CO_2 emissions, it has generally received less public and private support than other low-carbon technologies. For policy makers it often means high up-front costs and few near-term benefits. CCS policies will pay off, but depend on a successful transition to a low-carbon economy and wide acceptance of carbon prices (or equivalent policies) at levels that change investment patterns. The public, if they are aware of CCS at all, can be sceptical of end-of-pipe

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[1] CO_2 capture from air can remove CO_2 from the atmosphere, unlike other mitigation techniques that prevent its emission to the atmosphere. It uses chemical or physical techniques or the cultivation of sustainable biomass, which can in turn be used for energy purposes and coupled with CCS (bioenergy with CCS is currently the most advanced technical option in this category). The CO_2 can then be kept out of the atmosphere through geological or mineral CO_2 storage. As CO_2 is present in the atmosphere at very low concentrations, its capture from air is more energy-intensive than from emission sources. Despite the relatively high cost, air capture may become desirable if atmospheric CO_2 stocks rise above tolerable levels or to offset emissions from sources to which CCS cannot be applied, e.g. vehicular transport.

solutions apparently promoted by the same industries that they hold responsible for the problem. Furthermore, some features of other successful innovation systems, such as introduction of novel technologies by new and disruptive market players, or initial customers willing to pay sufficient premiums for the perceived benefits of the technology, cannot be relied upon for CCS.

To foster the adoption of CCS in the face of these hurdles, the CCS industry needs to be built from the bottom up. Finding specific regions and sectors where market, policy and social drivers can be aligned to enable the use of CCS technologies may be more successful than attempting to correct all market failures from the outset. Governments, industry and other partners need to pursue a three-part innovation strategy.[2] The three parts are:

- taking advantage of early opportunities in sectors and regions where CCS technology and emissions abatement costs can be most easily borne
- pursuing technological changes that could reduce the costs and improve the performance of CO_2 capture for electricity generation
- exploring innovative ways to keep CO_2 storage costs low.

CCS is already viable in several regions and applications where costs, policy and commercial opportunities align. These initial "sweet spots" for CCS are primarily in industrial applications, including hydrogen production, natural gas processing and biofuels production. These early opportunities will expand in number, market size and geographical extent, as climate mitigation actions become an increasingly important part of the global commercial landscape. Each project generates experience that can improve the performance of subsequent generations of CCS projects, including in other sectors and regions.

The electricity sector, which represents the largest single opportunity for CCS deployment, also poses a particular technology challenge. Electricity systems are in transition. Some regions of the world are shifting away from traditional utility models and "base-load" operating conditions and – especially in many OECD countries – towards higher levels of variable renewable capacity with low operating costs. CCS-equipped plants will have higher operating costs than many other low-carbon options and could therefore face strong competition for operating hours. These changes mean that CCS does not enable, as is sometimes claimed, fossil fuel-fired "business as usual". Instead, it offers a valuable element of the transition towards the 2DS: dispatchable electricity with CO_2 emissions more than 70% lower than those from natural gas plants today. But CCS will be viable only where these attributes are valued and the benefits of its flexibility for the electricity system are demonstrated.

The innovation needs and opportunities in CO_2 transport and storage are less obvious. CO_2 transport by pipeline is a well-known technology, with over 6 600 kilometres (km) of pipeline in North America moving more than 60 million tonnes of CO_2 ($MtCO_2$) annually. CO_2 transport and storage are also commonly considered to be comparatively small components of overall costs of CCS-equipped facilities.[3] But CO_2 storage entails significant up-front risks, and without innovation, geological conditions could lead to rising – not declining – storage costs in the long run.

The recent commercial operation of a power plant equipped with CO_2 capture in Canada is a major advance. Without more such real-world experience, however, there is a risk that CCS

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[2] This chapter is not a comprehensive overview of CCS status, technologies or policies. Reviews of many of these can be found in other IEA publications or via the reference list.

[3] For coal-fired power generation throughout the 2DS time period, these elements of the CCS value chain represent no more than 5% of costs per megawatt hour (MWh), compared with 10% to 25% for CO_2 capture.

is used more as a promise of a solution that could be implemented in the future than as a major part of the solution in practice. In parallel, some other low-carbon technologies such as photovoltaics and electricity storage are improving in terms of performance and cost, thus making the case for CCS more challenging. The gap between the rhetoric on the need for CCS and the action that would deliver it needs to be closed.

The innovation path for CCS: Starting with "sweet spots"

Technological change can be messy, complex and long-term. Hindsight has a habit of making past transitions appear neat and inevitable – but it took 60 years from the first commercial production of oil before it captured 10% of the primary energy market, and then another two decades to reach 30%.[4] Decarbonising is likely to be just as complex as previous energy system transitions, if not more so, involving the acceleration and reconfiguration of many economic, technological, social and political factors.

The good news is that the energy system is already evolving towards a more sustainable model in many regions. CCS operates today in a limited number of early opportunities, or sweet spots, mostly in industrial applications (non-electricity generation) where CO_2 capture costs are lower (Box 5.1).

Box 5.1 "Sweet spots" give new technologies a chance to thrive

Early opportunities for first deployment of a new technology, or new use of existing technologies, can provide shelter from an otherwise hostile commercial environment. These "sweet spots" (also called technological niches) are limited in scale but allow the technology to compete with more mature options and attract the learning and resources that will nurture them. If they are successful, they will spill over into new opportunities and find new users. Some sweet spots emerge from market forces, including economic disruptions such as geopolitical factors, demographics, technology breakthroughs or changing social preferences. But others need to be created by dedicated government innovation policies, especially where there is a public benefit to deployment and market uncertainty. As the technology blossoms in a growing variety of such opportunities, it gradually moves into the mainstream where it can compete for mass-market applications. Within the energy system, examples include early opportunities for offshore wind in Denmark, bioethanol in Brazil and electric buses in China.

It is crucial to recognise that the sweet spot where a technology emerges may be in a very different sector from the larger-scale markets that follow. Gas turbines developed for aircraft in the early 20th century offered a 35% increase in power output (Islas, 1997). But when gas turbines were first proposed for electricity generation in the late 1940s, their 5 megawatt (MW) scale and 20% efficiency could not match the improving steam turbines of the day (Watson, 2004). They were attractive for industrial applications, however; and for electricity backup by the 1960s; and for combined-cycle, large-scale power generation by the 1980s. The conversion of CO_2 capture from serving high-value chemical uses to widespread power plant pollution control represents a similar transition between applications with different technical, economic and risk requirements.

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[4] Liquefied natural gas (LNG) storage took half a century to progress from the first commercial example to 5% of the gas export market. Horizontal drilling took over six decades to reach around 5% of all developmental oil wells drilled annually. UK coal consumption peaked in 1913 but took almost five decades to fall to half of its peak value.

These existing early opportunities open a path for CCS deployment by providing commercial experience and enabling cost reductions. The innovation process that drives CCS technology use in an increasing number of sectors and regions is a virtuous circle of market creation that generates performance and cost improvements. These improvements in turn open up new markets in other sectors and regions where the gap between current technology costs and the willingness of governments and consumers to invest in climate change mitigation is higher. In the 2DS, willingness to invest in the benefits of reduced emissions increases in all countries over time, which will be reflected in policies such as carbon pricing.

Furthermore, unanticipated opportunities will arise as the learning process provides lessons applicable to CCS. For example, enhanced water recovery,[5] mentioned in the 2014 US-China Joint Announcement on Climate Change and Clean Energy Cooperation (White House, 2014), has recently come to the fore and could offer the double benefit of CO_2 abatement and fresh water production.

The necessary conditions can be summarised as a convergence of three factors that reduce the investment hurdle and project risk for each subsequent project:

- **Learning-by-doing** reduces technology costs and raises performance, especially in early opportunities, or sweet spots, where the learning rate can be expected to be steepest.
- **Learning-by-researching** in laboratories, research institutions and industry-led projects introduces lower-cost and better-performing technologies.
- **Market creation requires** policy development, macroeconomic and societal factors to raise the market value of CCS technologies. Policy is central to expanding the number and size of the commercial opportunities by ensuring that knowledge “spills over” to other sectors and regions, and by creating profitable markets for CCS technologies. These markets may be small initially but must merge with broader commodity markets over time, for example through carbon pricing.

These three factors are closely related. Market creation stimulates both types of learning. Unless each factor is supported, the learning and deployment rates for CCS in the 2DS will not be met.

CCS technologies are already deployed where conditions are aligned

The first large-scale opportunities for CO_2 capture arose in the 1970s in North America from the demand for CO_2 for enhanced oil recovery (CO_2-EOR), which was supported by government policies on national energy security. CO_2 could be captured from hydrogen production, synthetic fuels production and natural gas processing[6] at a cost that could compete with CO_2 from natural underground deposits, and plants at the 1 $MtCO_2$/yr scale were commercially developed. Over 12 $MtCO_2$/yr are now captured in the United States from fossil fuel operations and transported, along with around 50 $MtCO_2$/yr produced directly from underground deposits, through 6 600 km of pipelines. Thirty years of industrial experience with handling and injecting CO_2 has provided a significant body of knowledge.

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[5] In conjunction with CO_2 injection for permanent storage, brine can be removed from the same saline formations and, if treated, the resulting fresh water can be used for power plant cooling, agricultural water, potable water, oilfield make-up water and other uses (NETL, 2014). The reservoir pressure of the water reduces desalination costs compared with seawater. In addition, the removal of brine presents the potential for added benefits to CO_2 storage operations through pressure management. While the concept is well-developed, the process is not currently in operation in combination with CCS.

[6] CO_2 is captured wherever natural gas is extracted with a CO_2 content higher than pipeline or LNG standards, which usually limits CO_2 to around 2% by volume for pipelines and lower for LNG.

Table 5.1 Attributes defining the initial sweet spots for a selection of existing projects using CCS technologies

Start year	Project	Sector	Steps in the CCS chain deployed	Primary product cost increase	Commercial foundation	Social/political foundation
1972	Val Verde, United States	Gas processing	Capture, injection	Low	CO_2 sales (EOR)	
1978	Searles Valley, United States	Electricity/ chemicals	Capture	Low	CO_2 sales (800 tCO_2/day for soda ash)	
1996	Sleipner, Norway	Gas processing	Capture, injection, monitoring	Low	CO_2 tax, technology development	Technology leadership, climate commitment, fossil fuel revenues
2000	Great Plains, United States; Weyburn, Canada	Refining (coal-to-liquids)	Capture, transport, injection	Low	CO_2 sales (EOR)	
2013	Lula, Brazil	Gas processing	Capture, injection	Low	CO_2 sales (EOR)	
2013	Port Arthur, United States	Refining	Capture, transport, injection	Low	CO_2 sales (EOR), public grant, tax credits, technology development	Climate action, technology leadership
2014	Boundary Dam, Canada	Electricity	Capture, transport, injection	High	CO_2 sales (EOR), public grant, emissions standard, regulated utility rates, technology learning	Climate action, low-cost coal resource
2015	Gorgon, Australia	Gas processing	Capture, injection, monitoring	Low	State mandate, technology development	Fossil fuel revenues, climate commitment
2015	Illinois Industrial CCS Project, United States	Biofuels	Capture, transport, injection, monitoring	Low	Public grant, tax credits	Climate action, technology leadership
2015	Quest, Canada	Refining (oil sands upgrading)	Capture, transport, injection, monitoring	Low	CO_2 tax, public grant, technology development	Climate commitment, fossil fuel revenues
2015	Uthmaniyah, Saudi Arabia	Gas processing	Capture, transport, injection, monitoring	Low	Oil sales (EOR), state-owned company, technology learning	Fossil fuel revenues, climate action
2016	Abu Dhabi project, United Arab Emirates	Iron and steel	Capture, transport, injection	Medium	CO_2 sales (EOR), state-owned company	Fossil fuel revenues, climate action
2016	Kemper County, United States	Electricity	Capture, transport, injection	High	CO_2 sales (EOR), public grant, tax credits, regulated utility rates, technology development	Low-cost coal resource, climate action, technology leadership
2016	Parish, United States	Electricity	Capture, transport, injection	High	Oil sales (EOR), public grant, tax credits, emissions standard, technology learning	Climate action, technology leadership

A subsequent commercial sweet spot arose in the 1990s in Norway from the combination of government climate policy (a CO_2 emissions tax), low-cost CO_2 capture potential in gas processing and favourable geology for permanent CO_2 storage. The abatement cost of compression and storage in a local geological formation of CO_2 captured from natural gas processing can be as low as USD 14 per tonne of CO_2 (tCO_2) (SBC Energy Institute, 2013). By comparison, abatement costs for onshore wind and rooftop solar are in the range of USD 30/tCO_2 to USD 50/tCO_2, while electric vehicles and concentrated solar power could be in the range of USD 80/tCO_2 to USD 100/tCO_2 by 2030, depending on prevailing electricity supply mixes (IEA, 2012).

In the early 2000s, CCS was made a permit condition of a large Australian liquefied natural gas (LNG) project with high expected returns and emissions. Since then, the political prioritisation of CO_2 emission reductions and/or continued demand for CO_2 for EOR[7] has created additional opportunities for investment in CO_2 capture from hydrogen production (Canada and the United States), gas processing (Brazil, Saudi Arabia and the United States), bioethanol production (the United States) and iron manufacturing (Abu Dhabi).

Looking at a selection of projects that use CCS technologies on a large scale, the attributes that underpin these opportunities are apparent (Table 5.1). To offset capture and transport costs, stable revenues from selling CO_2 for industrial uses have been vital in most cases. CO_2 utilisation, including storage of CO_2 via EOR, is likely to continue to play a role in CCS development, and also CCS deployment if associated emissions reductions are verified and rewarded.

What makes CCS technologies competitive in some situations today?

The additional costs of CCS technologies in operation or construction have generally represented a small proportion of the facilities' production costs or profit margins, often because the separation of CO_2 is required in the production process. Where these costs have been significant, they have generally not been fully covered by operational revenue from EOR or climate policies but have been complemented by government grants for climate action and technology development. Monitoring of stored CO_2 – a key technical and regulatory aspect in the full CCS value chain – has notably been deployed only where the social and political foundation for the project has included robust government climate policy.

Commercial opportunities for CCS technologies all score highly on the following criteria:

- a clear opportunity for continued use or export of local fossil fuel resources
- located in regions with well-understood geology that is attractive for CO_2 storage, and with available expertise to utilise it
- a low expectation of near-term competition in the supply of the primary product (e.g. due to the stability of regulated electricity utilities)
- a low-risk political and social environment for CO_2 injection into deep geological formations, along with a predictable regulatory framework.

Additionally, one or more of the following criteria has also generally been met:

- a dependable revenue stream for CO_2 sales, for example for EOR
- the impact of CCS costs on profit margins is manageable (e.g. because the plant to be equipped with CCS is the lowest-cost producer in the market or can pass costs to consumers in a regulated market)

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[7] Especially given the expectation that prices for CO_2 from natural deposits will continue to rise due to scarcity.

- large volumes of relatively pure CO_2 are being vented from existing facilities due to inherent CO_2 separation processes
- an explicit national emissions reduction policy that includes reductions via CCS from relevant sectors
- strong government support for the development of CCS
- strategic benefits to operating CCS technologies, such as a boost to reputation or an advantage from being first in the field.

These factors have combined to increase public and private sector willingness to invest in CCS technologies. The more of these criteria a sector and region meets, the more likely the opportunity is to be sustainable, i.e. to be commercially attractive for the full lifetime of the plant and to generate opportunities for subsequent plants to build an industry over time. Without such sustainability, the share of public funding may need to be much higher, and there is a risk that learning from early projects will not be passed on efficiently.

Where can the next markets for CCS be developed?

As sweet spots are so important to the innovation process for CCS, there will be high pay-offs wherever governments can create them. The next opportunities for projects can be created by policy interventions in sectors and regions where the gap is smallest between current CCS technology costs and the willingness of governments and firms to invest in climate change mitigation. Many such opportunities are in industrial applications, including gas processing and hydrogen production, as introduced above, especially if the CO_2 can be sold for EOR. Large-scale bioethanol is another example of commercial CO_2 separation that could be combined with storage instead of venting, as is biogas upgrading, albeit in smaller volumes.

The policies that can create sweet spots are highly dependent on the application and region. For example, where low-cost CO_2 capture can be cost-effectively coupled with EOR, climate policy incentives (e.g. carbon pricing) may only need to cover costs such as storage site monitoring. Where sufficient resource rents exist for producers to accommodate CCS costs within profit margins, regulatory decisions, standards or carbon pricing that effectively compel use of CCS could be used. Regulatory tools that compel CCS could also be used where trade barriers exist for reasons of geography or monopoly, but only if costs can be passed on to consumers. These approaches could be combined with grants or tax breaks to cover residual technology risk or other investment gaps.

For gas processing, it is likely that CCS would be widely used to control emissions under any climate change mitigation scenario. A recent study estimates that 313 $MtCO_2$/yr could be captured and stored (instead of captured and vented) from existing and planned gas processing operations by 2020 (Zakkour, Dixon and Cook, 2011). Furthermore, this sector has existing expertise in CO_2 control and geological management that can be transferred to CCS.

The CO_2 content in the raw gas processed at the Sleipner CCS project in Norway is up to 9% and Australia's Gorgon gas field has a CO_2 content of around 13%, while in other Australian fields it is 2% to 17%. In Wyoming and Colorado – where there are nearly 50 existing and planned gas processors – the CO_2 content can be up to 65% (DiPietro, 2012). Brazil's pre-salt operations (CO_2 content from 8% to 15%), Canada's Horn River Shale (12% CO_2) and Indonesia's Natuna field (up to 70%) are examples of how the frontiers of the oil and gas industry are being pushed towards formations where natural gas is of lower quality. To meet natural gas pipeline and LNG standards of up to 2% CO_2 by volume, CO_2 from these fields needs to be separated. To avoid venting the CO_2 to the atmosphere it would then need to be stored.

In sectors such as steel, cement, refining and chemicals production, profit margins and exposure to international trade mean that the costs of CCS cannot be absorbed easily. In addition, their CO_2 capture costs are generally higher than CO_2 users (e.g. EOR operators) are currently willing to pay. Thus, with the exceptions of direct reduced iron and hydrogen production, where costs are lower, higher shares of public funding would probably be needed to create sustainable opportunities for CCS.

Growth markets, including Asian countries that are industrialising rapidly on the basis of increased fossil fuel use, are regions where markets for CCS technologies could emerge in the near term. Twelve CCS projects at commercial scale are under development in China (see Chapter 8). The scale of China's economic activity, its energy mix and gas prices that are anticipated to remain high relative to coal prices, make it a potentially crucial market for CCS. Both national and bilateral initiatives as well as instruments being developed within the UNFCCC could provide opportunities to create important initial projects and markets for CCS in OECD non-member economies.

Are there sweet spots in the electricity sector?

CO_2 capture from coal and gas combustion has a long history in several sectors, but only recently for the purposes of climate change mitigation. Demand for relatively small quantities of CO_2 for beverages, food, urea and soda ash underpinned early commercial investments in post-combustion capture plants. For example, in 1976 the Searles Valley Minerals plant in California started using 800 tCO_2 per day of CO_2 captured using amine solvents from a coal-fired power plant to make soda ash. By 2009, at least 0.5 $MtCO_2$/yr were being captured in the United States for food, beverage and chemicals customers using post-combustion processes on coal and gas flue gases (US EPA, 2010).

There is a substantial difference between these early opportunities for post-combustion capture and widespread CCS, however. While these initial plants served customers in markets where the USD 50/tCO_2 or more cost of CO_2 capture could be absorbed and the commercial risks could be offset by the potential profits, power plant operators do not have the same profit margins or appetite for risk. In addition, energy used for CO_2 capture has a high opportunity cost for a power plant, raising the cost of CO_2 "avoidance" above that which would be estimated from CO_2 capture costs alone. Transferring technology from smaller-scale, niche commercial applications to the electricity sector requires dramatic reductions in cost and risk. Climate policies are generally not yet strict enough to guarantee returns on CCS investments. Unit profit margins in the electricity sector are traditionally not high and investors are risk-averse. Additionally, CCS raises operating costs, potentially eroding operating hours and revenue if market conditions and design are not favourable.

Since the early 1990s, the electricity sector has been examining the potential of CCS technologies, which have been pushed to improve performance for this potentially huge new market (see next section). At the same time, supportive political, societal and geographical factors have coincided in places such as Canada, the United Kingdom and the United States. Investors proceeded with power plants capturing over 1 $MtCO_2$/yr in Saskatchewan, Canada (Boundary Dam), Mississippi (Kemper County) and Texas (Parish) because of favourable alignments of regulations on the CO_2 intensity of electricity; customers for CO_2 for EOR; access to long-term contracts for local coal; government funds and tax breaks to cover additional costs of technology development and emissions mitigation; and ability to operate as base load to reduce risks of first-of-a-kind plants.

While the electricity sector does not generally yet represent a sweet spot, plants where these factors align can now present early market opportunities alongside those in other sectors. It is important that they are joined by others to generate continual learning-by-doing. As with other innovative technologies and technology transfers to new sectors with different characteristics, there can be limits to how fast learning can proceed. This is especially true for large-scale, capital-intensive technologies. Each new application or plant needs to operate for several years so that experience can be fed into the next generation.[8] Achieving the performance and risk improvements demanded by the electricity sector may require several generations of comparable plants, each operating for at least a few years in supportive market environments. So it is vital that experiences from new plants be shared as widely as possible to minimise this initial period of a decade or more when costs can be reduced most quickly.

Achieving cost reductions in the electricity sector

For CCS to evolve beyond early opportunities, its costs must steadily fall and its performance improve so that it can compete in markets with high CO_2 abatement potential. In these markets – such as electricity, steel and cement – profit margins are low, assets are long-lived and capital-intensive, and processes and products are highly standardised. In the 2DS, CCS costs decline as deployment rises, as is already happening for some other technologies with which CCS competes in the electricity sector (Riahi et al., 2004). This section considers this cost trajectory and technologies that it may favour.

In the 2DS, costs decline as experience increases

The relationship between cumulative experience (expressed as installed capacity or cumulative output) and costs is called the learning rate. It is the percentage cost reduction for each doubling of the cumulative capacity or production.[9] For power generation applications in the 2DS, average learning rates are assumed to be around 8% for capital expenditure and 4% for efficiency (Figure 5.2). This means that until 2030, as several generations of technology are used and improved, the capital cost premium tumbles by 30% as capacity doubles several times over. After 2030, CCS costs in the 2DS are much lower than they are today, but deployment of CCS-equipped power plants will still require strong climate policies – such as a carbon price of USD 50/tCO_2 or more in 2050 in the United States. In the 2DS, CCS is deployed at a steady rate, which allows industry to maintain and build competency in the relevant areas.

The learning rate reflects experience gained through both learning-by-doing and learning-by-researching. Learning-by-doing arises from familiarity of designers and operators, development of competitive supply chains, standardisation, and reduction of finance risk. It leads to both technical and non-technical improvements.

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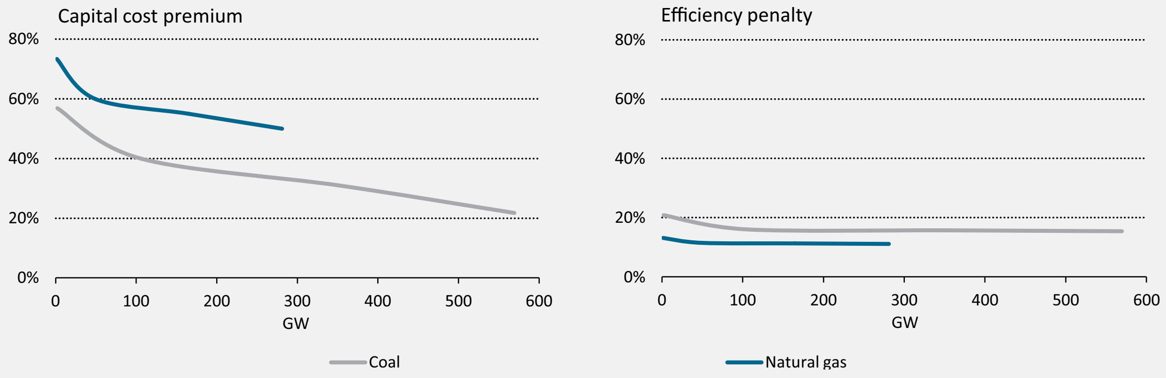
[8] A minimum of 15 years from pilot scale to post-demonstration scale for a *successful* technology in the electricity sector has been suggested (Bhown, 2014). Financial markets may be prepared to consider technology risks to be overcome only once there are several exemplars of a given technology at large scale.

[9] It has been recorded to be around 10% during the development phase of a number of the major energy technologies over past decades (IEA, 2000). The rate tends to be higher for technologies with smaller unit sizes that can be mass-produced, such as batteries or photovoltaic panels, than for the large unit sizes of nuclear power plants and refineries for which new plants are more dispersed in time and space. For CCS, 12% has been suggested for capital costs (Rubin et al., 2004).

Figure 5.2 The impact of adding CO_2 capture on power plant cost and efficiency in the 2DS



Note: GW = gigawatt.

Key point *As the installed capacity of CCS-equipped power plants grows in the 2DS, the efficiency penalty and capital cost premium fall.*

As with learning-by-doing, learning-by-researching benefits from growth in installed capacity as greater confidence in the market for a technology stimulates others to join the search for better solutions. It also benefits from new data and technology testing opportunities that arise due to increased deployment. In terms of government support, it is stimulated by "technology push" policies, such as public funding of R&D, and "market pull" policies, such as carbon pricing or tax credits that create markets that reward innovators. For example, patents for sulphur dioxide removal in coal-fired power plants rose around 60% in the United States in 1971, the year that legislation created a market for the technology, and remained high until the late 1990s (Taylor, Rubin and Hounshell, 2003). Learning by researching requires up-front investment in projects at laboratory, pilot and demonstration stages when future returns are uncertain.

The learning rate does not control for all the many real-world factors that can influence costs, such as labour shortages and rising costs for materials, which have caused cost escalations in recent energy infrastructure projects. In addition, if there are significant interruptions in the process of gathering experience, learning can decline and even go into reverse. Learning rates that consider only cumulative capacity or output do not account for this "forgetting by not doing" (McDonald and Schrattenholzer, 2001). To maximise learning, steady deployment is vital.

The impact of learning on the cost of electricity from CCS-equipped plants

The levelised cost of electricity (LCOE) from CCS-equipped plants goes down over time in the 2DS, as learning reduces capital cost and improves efficiency, and fuel prices change. Demand for coal declines in the 2DS and coal prices fall, thus improving the competiveness of coal-fired CCS-equipped power plants. At the same time, rising carbon prices – the charges that emitters must pay per tonne of CO_2 – make CCS more attractive than unabated fossil fuel use.[10] But they increase CCS costs somewhat, assuming CO_2 capture

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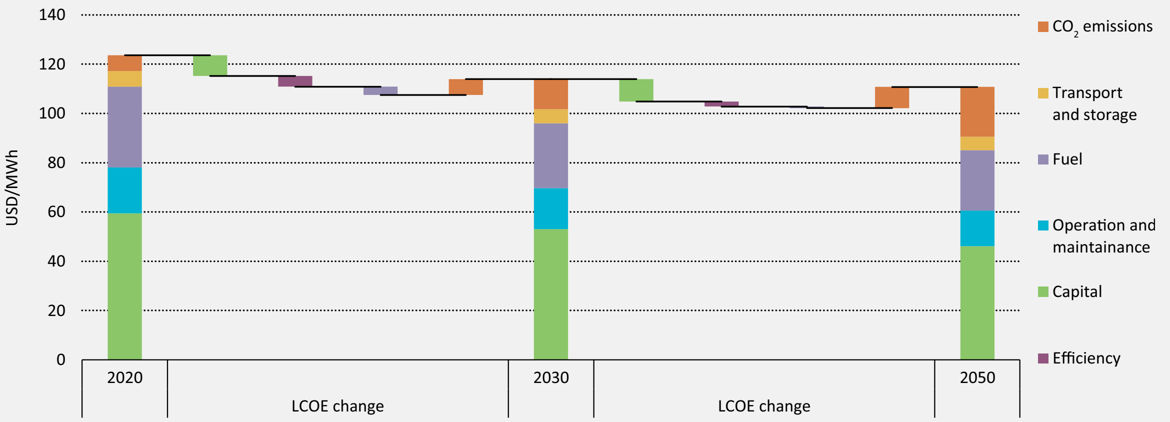
[10] Unabated fossil fuel use refers to combustion processes that do not apply CCS to abate CO_2 emissions. Before the application of CO_2 abatement technologies, industrial processes generating CO_2 from chemical or biological processes can also be considered to be unabated. In the case of coal, so-called high efficiency low emissions (HELE) technologies are considered unabated unless combined with CCS.

rates remain at around 90%: charges must still be paid for the 10% of CO_2 that is not captured (Figure 5.3). While not modelled in the 2DS, this could foster higher capture rates in retrofits and new plants.

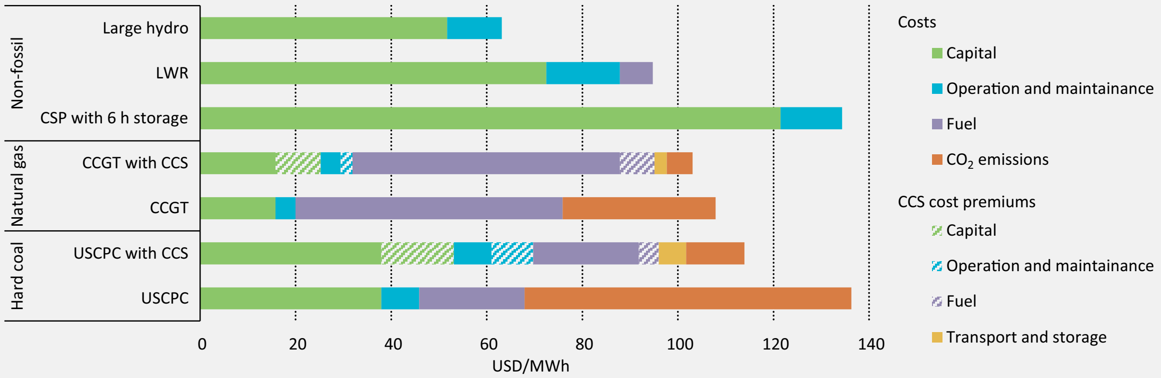
Figure 5.3 LCOE change in the 2DS of an ultra-supercritical pulverised coal (USCPC) power plant equipped with CCS



Key point *The LCOE of coal-fired CCS plants falls in the 2DS due to a combination of factors, of which capital cost reductions play the largest role.*

In the 2DS, learning reduces the overnight capital cost of capture-equipped power generation by about 20% between 2020 and 2050. Over the same period, the efficiency of generation from USCPC plants equipped with CCS increases to 44%, only 8 percentage points less than the most efficient coal-fired power plant without CCS. The cost of electricity from CCS-equipped plants is likely to continue to be dominated by capital costs in the case of USCPC and operational costs (i.e. fuel) in the case of gas-fired generation (Figure 5.4).

Figure 5.4 LCOE of CCS-equipped power plants and comparable technologies in 2030 2DS Europe



Notes: LWR = light water reactor; CSP = concentrated solar power; CCGT = combined-cycle gas turbine. The LCOE for fossil fuel and nuclear technologies is calculated on the basis of a 75% capacity factor; the values for CSP with 6 h storage and large hydro assume a 40% capacity factor.

Key point *Innovation, falling fuel prices and rising CO_2 prices reduce costs of CCS-equipped power generation to a level where they are competitive with other dispatchable, low-carbon options in the 2DS.*

Capital costs can be reduced by modularisation, standardisation of components, establishment of supply chains, reduced construction times, lower costs of borrowing, innovative use of materials, reductions in contingency costs, and novel process designs and equipment. Operational costs will be reduced principally by lower separation energy requirements, improved process integration and process controls, reduced maintenance, and increased reliability. The emergence of alternative power generation cycles or approaches to gas separation (e.g. oxygen, hydrogen or CO_2 separation) via learning-by-researching could also play a role in achieving the 2DS learning rate.

While LCOE allows comparison of costs among technologies, it may be an unreliable metric when comparing technologies at different stages of maturity. It can also be a misleading measure of technologies that perform different roles in an electricity system and that need to be valued based on their contribution to system reliability, flexibility and cost. Other ways of evaluating CCS include the cost of CO_2 avoided and the technology readiness level (TRL) (Box 5.2).

In the 2DS, capacity factors of coal and gas plants fall in most regions as variable renewables become more cost-competitive in the portfolio of decarbonisation options and are more widely deployed. In some markets, the rapid growth in variable renewables has already led to reduced capacity factors for fossil fuel plants. But the expansion of variable renewables will raise the value of dispatchable generation that can operate flexibly and with low emissions. CCS-equipped power plants could provide the necessary flexibility, diversity and frequency control – and thus limit the costs of phasing out installed fossil fuel capacity – but ensuring flexibility involves trade-offs between revenue from higher electricity prices, emissions penalties (if flexibility is achieved by reducing capture rates) and additional costs of flexible operation.[11]

How does this cost evolution compare with government targets?

2DS learning rates for CCS are broadly in line with several medium-term targets or aspirations that have been developed for governments in Europe and the United States (Figure 5.2 and Table 5.2). These targets are considered ambitious, requiring technological breakthroughs. For example, the United States (US) 2030 goals are considered to require so-called transformational technology.[12] This indicates that both learning-by-doing and learning-by-researching are likely to be needed to play significant roles in achieving the 2DS learning rate for CCS.

Recent experience with CCS cost estimations

Looking at normalised estimates for LCOE from future new-build capture-equipped coal power plants (Finkenrath, 2011), there has been a slight upward trend, consistent with increases for comparable plants without capture (Figure 5.5). Today, investment costs for one operational plant, plus estimates from a handful of detailed engineering and design studies, show a range of costs several times higher than the 2DS cost assumptions for

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[11] For more information on, see online summary “CCS-equipped power generation can be flexible, but it comes at a cost”, available at www.iea.org/etp/etp2015/secure/CCS_flexibility.

[12] “Transformational technologies include technology components that are in the early stage of development or are conceptual that offer the potential for improvements in cost and performance beyond those expected from 2nd-generation technologies [that will be ready for demonstration in the 2020-2025 timeframe]. The development and scale up of these ‘transformational’ technologies are expected to occur in the 2016-2030 timeframe, and demonstration projects are expected to be initiated in the 2030-2035 time period” (US DOE, 2013).

2020, and a significantly higher LCOE than that shown in Figure 5.3. To a large extent, this reflects the first-of-a-kind nature of these plants. However, it is common – and even normal – for costs to increase as designs are refined during development and initial deployment (Merrow, 1988; Yeh and Rubin, 2012).

Box 5.2 Metrics to evaluate CCS and other low-carbon technologies

The cost of CO_2 avoided, LCOE and TRL are three metrics that can be used to compare CCS technologies. Each has strengths and weaknesses and will be more or less relevant depending on the type of comparison and the maturity of the technology.

The cost of avoiding a tonne of CO_2 emissions indicates the carbon price above which a CCS-equipped plant would be more attractive than a reference plant. It is calculated by dividing the difference in LCOE between two generation options – at least one of which would be CCS-equipped – by the difference in their emissions rates. The choice of the reference plant therefore strongly influences the result (Rubin, 2012); it is usually a power plant nearly identical in design to the CCS-equipped plant.

The cost of CO_2 avoided is only an informative metric when unabated coal- or gas-fired plants are a realistic alternative in a region. As CCS becomes a mainstream option in the 2DS, investments in unabated fossil fuel plants become more marginal, and evaluating a CCS-equipped plant by comparing it to a state-of-the-art pulverised coal plant will be increasingly irrelevant.

LCOE has historically been a basis for investing in new power plants in regulated markets. Calculating the LCOE for plants with 30-year lifetimes requires estimating fuel prices, carbon prices (or emissions regulations) and capacity factors. LCOE is only useful to compare generators with similar attributes, for example dispatchable generators or demand management options. LCOE calculations do not account for large differences in the value of electricity over time (Joskow, 2011). In regions with growing shares of variable renewables such as wind and solar energy, variations in the value of electricity from different sources may increase over time. Capacity factors of dispatchable generation plants may fall, resulting in higher LCOE, even as their value to the system at peak times increases. The emissions, flexibility and operational benefits of CCS-equipped plants could make them natural competitors to large hydro, tidal, nuclear, biomass and inter-seasonal electricity storage. The value of CCS as part of a truly low-carbon system is a key consideration for policy makers.

For CCS technologies at early stages of development, it is often not possible to estimate future LCOE and is more appropriate to look at reliable technical measures of performance that will be valued in future electricity markets (e.g. efficiency, ramp rates, flow sheet complexity). Experience shows that the estimated cost of a technology at an early stage of development should be higher than technical studies might suggest, as cost contingencies are recommended to reflect uncertainties.

TRLs can be used to assess how far a technology is from market, and hence the uncertainties in other evaluation metrics. Developed by the National Aeronautics and Space Administration (NASA) in the 1970s (NASA, 1977), the TRLs have been adapted slightly to the R&D of electric technologies by the Electric Power Research Institute (EPRI, 2011; Engel et al., 2012). The TRL scale progresses from exploratory research that transfers basic science to laboratory applications (TRL 1), through early field demonstration and system refinement (TRL 6), to complete system demonstration in an operational environment (TRL 7) and wide-scale commercial deployment (TRL 9).

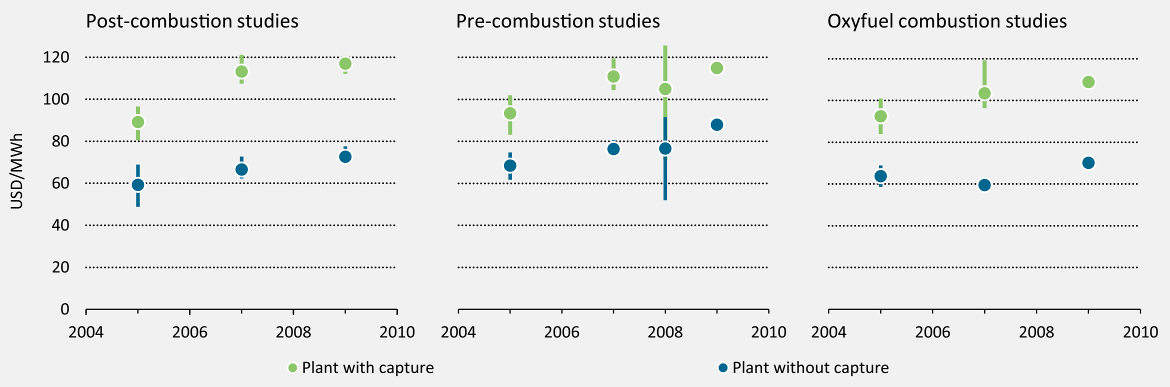
Table 5.2 Targets for cost reductions from three governmental bodies

Area	Targets			
US DOE Carbon Capture Research Program				
	Cost of capture (USD/tCO$_2$)		LCOE reduction from 2011 baseline	
	2025	2030	2025	2030
Coal	42	26	20%	30%
European Industrial Initiative on CCS				
	Avoidance cost (USD/tCO$_2$)	LCOE (USD/MWh)	LHV efficiency with capture	
	2025		2020	2025
Coal	55	108	36%	38%
Natural gas	162	153		
UK CCS Cost Reduction Task Force				
	LCOE (USD/MWh)			
	2020 (FID)		2028 (FID)	
Coal	153		137	
Natural gas	143		131	

Notes: kW = kilowatt; LHV = low heating value; FID = final investment decision. Costs adjusted to real 2013 USD. United Kingdom (UK) and United States (US) costs are for plants equipped with post-combustion CO$_2$ capture. Costs of CO$_2$ transport, storage and CO$_2$ pricing are not included.

Sources: US DOE (2013), *Carbon Capture Technology Program Plan*, DOE, Washington, DC; US DOE (2014) personal communication; EC (2013), *European Industrial Initiative on CO$_2$ Capture and Storage (CCS) Implementation Plan 2013-2015*, European Commission, Brussels; UK Carbon Capture and Storage Cost Reduction Task Force (2013), *The Potential for Reducing the Costs of CCS in the UK*, Final Report, CCS Cost Reduction Task Force, London.

Figure 5.5 Evolution of LCOE estimates for power plants with and without capture



Note: The points represent the average of normalised LCOE estimates provided in Finkenrath (2012), while the vertical lines represent the true range.

Key point *The estimated LCOE for future, new-build coal-fired power plants with and without capture increased in the five years from 2005 to 2009.*

In addition to site-specific issues – such as the design of the power cycle, local market conditions or available storage options – three kinds of factors can lead to the variation of prices over time and between studies (UKERC, 2012):

- **Exogenous factors** are external to a sector, such as increases in the costs of capital, steel, cement or copper due to high global demand or fluctuations in market prices.
- **Endogenous factors** emerge within a sector or region, such as supply chain bottlenecks that raise engineering, procurement and construction prices (e.g. labour, productivity). Unanticipated increases in regulatory costs can increase total costs.
- **Methodological factors** concern the way costs are estimated, which can also affect results (Rubin, 2012). Early-stage engineering assessments tend to be optimistic because of natural enthusiasm or the desire to secure public funding. Once costs are more rigorously calculated and risks are better understood, estimates tend to rise (Merrow, 1988).[13] Front-end engineering and design studies usually represent a site-specific appraisal of the necessary approach to capture, transport, storage and contingency costs.

It is usually assumed that these factors will increase costs in the early phase, but they can also reduce costs, for example if fuel price expectations fall. Furthermore, such uncertainty in the period before and during early deployment is not incompatible with longer-term cost reductions, as is expected for offshore wind (IEA, 2014c). CO_2 capture is not, after all, very different from other chemical and energy sector technologies, many of which have benefited during deployment from the standardisation of designs and development of efficient supply chains. This highlights the importance of comparing costs on a normalised basis and understanding factors that might influence future real-world costs.

The evolving CO_2 capture technology landscape

In power generation, there are three main approaches to capturing CO_2, which differ based on the power generation cycle: post-combustion, pre-combustion and oxy-fuel combustion capture. These can sometimes be combined to create hybrid routes. Integrated systems for post-combustion are at TRL 7, while the most advanced options for pre-combustion and oxy-fuel combustion are at TRL 6 and expected to reach TRL 7 by 2016 and 2019, respectively. For each approach, there are proposed technology improvements at earlier stages of development.

In post-combustion capture, CO_2 is separated from flue gases at the end of the power generation process. In oxy-fuel combustion, pure (or nearly pure) oxygen is used in place of air in the combustion process to yield a flue gas of high-concentration CO_2. A specific CO_2 separation step is not necessary, but there is an initial separation step for the extraction of oxygen from air, which largely determines the energy penalty – the extra energy required to incorporate CCS. In pre-combustion, CO_2 is removed from a mixture of hydrogen and CO_2 that is generated by gasification, or reforming, plus a shift reaction. This leaves a combustible gaseous fuel that can be used in a gas turbine.[14]

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[13] Before real project costs are revealed by private investment data, strategic underestimation of costs has been observed in competitions for public funds (Flyvbjerg, Holm and Buhl, 2002).

[14] This cycle, with the exception of the CO_2 capture step, is referred to as integrated gasification combined cycle (IGCC).

Improving the performance of post-combustion CO_2 capture

Post-combustion capture can be applied to new or existing coal- or gas-fired plants. The largest post-combustion capture plant began operating in 2014 at Boundary Dam, Saskatchewan. It has a net capacity of 110 megawatts electrical (MW_e) and is a retrofit and life extension of a unit built in 1969.

From 2010 to 2014, more than 400 GW of new coal-fired power plants came into operation globally (Platts, 2014). Representing around 8% of today's installed generation capacity, these new plants are likely to have more than 20 years of technical life remaining in 2030. Plants under construction today will have even more useful life remaining in 2030. This installed fleet of coal (and gas) plants represents a very large asset base, the emissions from which can be significantly reduced only by retrofitting CCS. In most cases, retrofitting would be accompanied by upgrades that would also extend the plant's total lifetime. In theory, post-combustion capture does not require a radical redesign of the power plant and is therefore the most promising retrofit solution.

Retrofitting an existing power plant with capture is attractive when it prevents the retirement of an asset or could otherwise increase its competitiveness in the market under climate policy.[15] The incremental capital expenditure of adding capture to an existing plant is considerably lower than the investment cost of a new capture-equipped power plant because the cost of the base plant is "sunk". This means that only the incremental cost of CCS needs to be covered by the revenue arising from the lifetime extension. Retrofitting may also be attractive where investments in new thermal plants with 40-year lifetimes are perceived to be particularly risky. Nonetheless, a retrofitted plant is likely to have a shorter life and higher operating costs than a new plant.[16] Attractiveness of retrofits will also be heavily influenced by the proximity of existing plants to available storage.

CO_2 separation technologies for post-combustion capture are relatively mature because they were developed as a source of CO_2 for the food and chemicals sectors and, later, EOR. The current industry standard for separating CO_2 from the flue gases of a power plant is amine solvent absorption, which has been operated commercially since the 1970s. It has recently been significantly improved for application as a climate change mitigation technology. New solvents and better plant integration have helped reduce the energy required to separate CO_2 from flue gas by 50% since 1990 (Figure 5.6). This has lowered the energy penalty of CO_2 capture when compared with an unabated power plant. This is generally expected to be 20% to 30% for plants built today.

There is scope to reduce further the energy required for CO_2 separation using amine solvents. Current operational performance is 10% to 25% higher than the absolute minimum heat requirement of today's commercial amine solvents. It is around ten times higher than the thermodynamic minimum for CO_2 separation from flue gas (Van Straelen and Geuzebroek, 2011), which indicates the limitations of amine solvents and explains the many research efforts into other non-amine approaches.[17] Achieving improvements in post-combustion capture in line with 2DS learning rates is likely to require a more integrated approach, taking into account capital costs and CO_2 compression requirements as well as separation energy.

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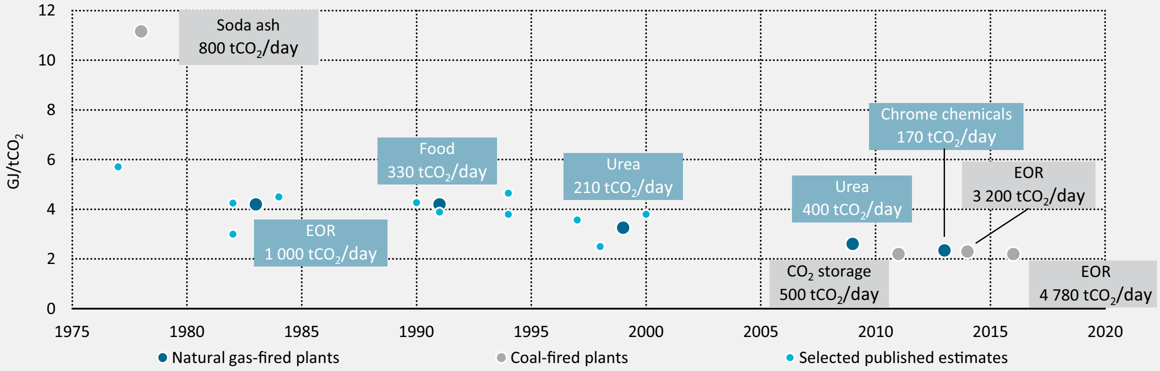
[15] In some cases, CO_2 sales for EOR or other uses may make retrofitting attractive without strict climate policy. Due to costs of CO_2 capture, and CO_2 storage monitoring, these are likely to be rare opportunities and geographically limited.

[16] New plants constructed today can be designed to be more "CCS ready", which can include allocation of space for the CO_2 capture plant, selection of the steam cycle to optimise performance after addition of capture, and identification of CO_2 storage. However, uncertainties regarding the timing of CCS addition and discounting of the future do not generally justify significant spending on up-front modifications in the absence of regulatory obligations. Thus, ensuring that retrofit can and will occur later in a plant's technical lifetime may require strong regulatory requirements.

[17] The thermodynamic minimum heat requirement for CO_2 separation from coal flue gases (12% to 14% CO_2) has been calculated to be 0.16 GJ/tCO_2 (Feron, 2009).

Figure 5.6 Improvements in CO_2 separation energy for post-combustion capture



Notes: GJ/tCO_2 = gigajoules per tonne of CO_2 separated. For constructed plants, end-uses of the captured CO_2 and annual capture rates are shown.
Sources: Rochelle, G. (2014), "From Lubbock, TX to Thompsons, TX: Amine scrubbing for commercial CO_2 capture from power plants", presentation at GHGT-12 conference, Austin, Texas, 8 October 2014; Yeh, S. and E. Rubin (2012), "A review of uncertainties in technology experience curves", *Energy Economics*, Vol. 34/3, Elsevier, Amsterdam, pp. 762-771.

Key point *The energy required to separate CO_2 from flue gas has declined by 50% since 1990 as research has focused more on CO_2 capture for climate change mitigation.*

The energy and capital costs of post-combustion CO_2 capture

CO_2 capture has a significant energy cost because of the low partial pressure of CO_2 in flue gas to be treated at power plants[18] and the high pressures needed for transport and storage.

For amine solvent absorption, the main energy-consuming step in the process is the regeneration of the solvent and the recovery of the pure CO_2 after it has been chemically captured (this occurs in the CO_2 stripper in Figure 5.7). Specifically, energy is required to: heat the solvent, the majority of which is water; liberate the CO_2 from the solvent to which it is chemically bound; and circulate the solvent. The additional requirements for amine-based systems are typically 0.4 GJ/tCO_2 for compression to 11 megapascals (MPa) and up to 0.1 GJ/tCO_2 for other needs, generally delivered as electricity (IPCC, 2005). The minimum energy requirement for compression from 0.1 MPa to 15 MPa is 0.24 GJ/tCO_2 (Feron, 2009).

Small improvements can have considerable benefits for performance and cost. The energy used for CO_2 capture usually comes from the power plant itself, leading to combustion of more fuel for a given unit of electricity output. So reducing the regeneration energy also reduces the amount of fuel used and hence the amount of CO_2 that needs to be captured. Regeneration energy can be reduced by reducing the water content of the solvent or reducing how tightly the CO_2 is bound to it. In addition, better integration between the capture system and the power cycle can minimise the loss of electrical power output while still achieving the needed heat input to the capture system.

The direct capital costs of post-combustion capture arise from the need for separation equipment that can bring large volumes of gas into contact with the solvent, as well as large, high-pressure compressors. Three technical improvements can lower costs: those

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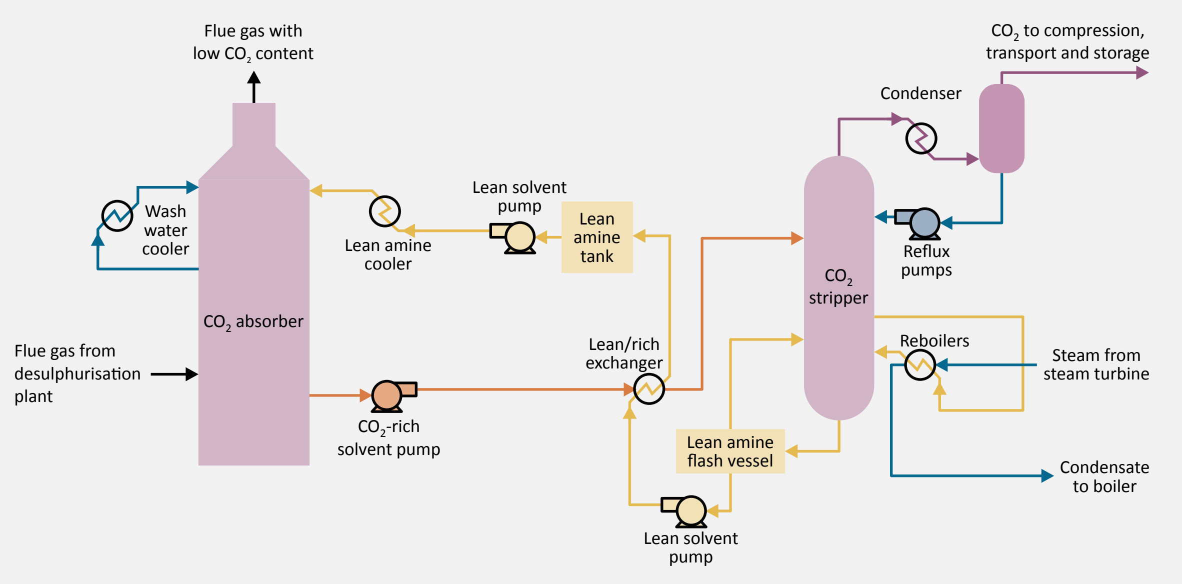
[18] In general, the energy to separate one substance from another increases as the concentration of the substance decreases.

that reduce or avoid regeneration energies without adding an equally energy-intensive process; those that decrease the pressure difference between the captured CO_2 and pipeline requirements; and those that reduce the capital costs of associated equipment.

Figure 5.7 Process flow diagram of post-combustion CO_2 capture using an amine solvent



Key point *Absorption processes using solvents for CO_2 capture are well developed and comprise two main processes: absorption of the CO_2 from flue gas and regeneration of the solvent using steam to desorb CO_2.*

Technologies that improve post-combustion capture

While amine solvents will continue to contribute some improvements, potential alternatives exist that could go beyond the promise of more advanced amine systems (Aldous et al., 2013; GHG IA, 2014; SINTEF, 2013). These alternatives differ in the particular cost elements of current technologies that they seek to reduce, such as capital costs, desorption energy and compression costs. They are also at different stages of development (Table 5.3). Since none of these technologies is clearly superior, some research organisations and governments are taking a prudent and balanced portfolio approach by investing in multiple options. Balanced portfolios include technologies representing both lower-risk, incremental improvements and higher-risk, more profound improvements.

Processes that capture CO_2 from flue gases by incorporating CO_2 into minerals or algae could also be developed in the 2DS time frame. Unlike those listed above, these processes do not deliver CO_2 as a gas for storage but produce materials that could be sold for fuel or construction materials. While there may be commercial advantages to such CO_2 “utilisation” approaches, understanding the associated emissions reduction is more complex if the use of the resulting material might lead to release of the CO_2 to the atmosphere (Bennett, Schroeder and McCoy, 2014). Mineralisation and algal capture approaches are currently at an early stage of development for post-combustion applications and face considerable challenges related to achieving power plant scales of operation (Sanna et al., 2014; GHG IA, 2014).

Table 5.3 Non-exhaustive list of advanced post-combustion CO_2 capture technologies and their features

CO_2 capture type	Key advantages	Potential disadvantages	Experience with power plant flue gas or in other sectors
Advanced non-amine aqueous solvents (e.g. ammonia, piperazine, amino acid salts)	Lower heat demand; leverages experience from amine solvents; lower solvent volatility (piperazine).	Performance improvements may not be large.	Chilled ammonia tested at 20 MW_e on coal in the United States (2009) and at 20 MW on gas and fluid catalytic cracker in Norway (2012). Piperazine tested at 0.1 MW_e in United States and Australia. Amino acid salts tested at 2 MW in Australia.
Calcium looping	Low-cost sorbent; spent sorbent may have commercial value.	Make-up stream of sorbent required; pure oxygen input may be needed; retrofits may be poorly optimised.	Tested at 1.9 MW_{th} in Chinese Taipei (2013) and at 1.7 MW_{th} in Spain.
Catalytic solvent activation, including enzymes	Smaller equipment (advanced absorption kinetics); lower regeneration energy.	Catalyst/enzyme costs (due to deactivation and instability); turndown issues with immobilized catalysts.	Projects under way to scale up to 0.1 MW_{th} in United States by 2016. CO_2 separation for biogas upgrading is more advanced.
Cryogenic fractionation	No hazardous chemicals; no impact on steam cycle (uses electrical energy); CO_2 delivered at close to pipeline pressure; potentially lower separation energy.	High equipment costs.	Proof of concept stage for post-combustion. Used extensively for separating gases from natural gas and air. Under development for CO_2 separation from natural gas.
Biphasic liquid solvents	Lower regeneration energy (no water in solvent regeneration); smaller equipment and solvent volumes; lower solvent degradation.	Additional equipment needed for phase separation; higher solvent costs; process design/ scale-up uncertainties (rich-phase viscosity presents technical challenges).	Carbamate-forming amine tested at approx. 5 kW_e scale in United States (2014). DMX-1 demixing solvent tested at bench/mini-pilot scale in Europe (2013).
Hybrid membrane/ absorption, membrane/ cryogenic	Lower separation energy; pre-treatment with membranes could reduce capital and solvents costs.	Trade-off between additional complexity and potentially incremental gains compared to single technologies; process design/scale-up uncertainties (e.g. material degradation challenges).	Membrane/cryogenic tested on coal at 0.1 MW_e anticipating 0.3 MW_e in United States in 2015. Already used to separate CO_2 during hydrogen production at commercial scale in Europe. Membrane/absorption tested at lab-scale; projects under way to scale up to 5-25 kW_e in United States by 2016.
Membranes	Smaller equipment (high contact areas); no hazardous chemicals; modular (possible incremental retrofits); no impact on steam cycle (uses electrical energy); high turndown ratios possible.	Often need an additional purification step; process design/scale-up uncertainties (equipment yet to be proven at sufficient scale); trade-off between CO_2 purity and capture rate.	Tested at 1 MW_e in United States (late 2014). Tested at 50 kW_{th} in Europe (2011). Used for CO_2 separation from natural gas since the 1980s.
Non-aqueous solvents	Lower regeneration energy (no water in solvent regeneration); lower solvent volatility; smaller equipment (high CO_2 loading).	High solvent cost; process design/scale-up uncertainties (high viscosity of rich phase and water balance maintenance).	Scale up of imidazole-amine hybrids to 0.5 MW_e anticipated in United States in 2015. Ionic liquids tested at bench scale.
Precipitating solvents	Reduced regeneration energy; smaller equipment (higher driving force for absorption); lower solvent degradation.	Increased solvent costs; need to handle solids; process design/scale-up uncertainties (novel equipment needed for absorbers with slurries).	Potassium carbonate system tested at ~0.05 MW_e in Australia. Scale up of carbamate solvent to 0.5 MW_e anticipated in United States in 2015.

CO_2 capture type	Key advantages	Potential disadvantages	Experience with power plant flue gas or in other sectors
Pressure swing adsorption (PSA) and vacuum swing adsorption	No hazardous chemicals; CO_2 delivered at close to pipeline pressure; no impact on steam cycle (uses electrical energy); smaller equipment (rapid PSA cycles); simple and flexible operation.	Trade-off between CO_2 purity and capture rate; pressure drop may limit efficiency.	Tested at bench scale. Used extensively and commercially for CO_2 separation in natural gas processing.
Supersonic inertial CO_2 extraction system	No hazardous chemicals; smaller equipment; low system volume.	High electrical demand for flue gas compression; need to handle solid CO_2; process design/scale-up uncertainties (slip gas minimisation); uncertainty regarding load following ability.	Proof of concept stage, aiming for scale up to 0.25 MW_{th} in United States by 2016.
Temperature swing adsorption (TSA) and electric swing adsorption	No hazardous chemicals; lower water demand; high purity CO_2 stream (compared to PSA); potentially fast kinetics and lower heat requirements.	Sorbent attrition/deactivation; high sorbent requirements; process design/scale-up uncertainties (e.g. heat recovery from solids and pressure drops).	Tested at 10 MW_e scale using potassium-based sorbent in Korea in 2014. Scale up of TSA with alumina adsorbents and solid sorbent-supported amines to 0.5-1 MW_e is under way in the United States. Used commercially for CO_2 separation in natural gas processing.

Notes: MW_{th} = megawatt thermal; kW_e = kilowatt electrical; kW_{th} = kilowatt thermal. MW scales of experience are indicative and in several cases derived from equivalent CO_2 or flue gas mass flows.

Research is also focusing on processes and techniques that could bring down the costs of existing solvent systems, which could also benefit the technologies in Table 5.3. For absorption systems, these techniques could include: membrane pre-treatment, novel dispersion/mass transfer equipment, absorber intercooling, stripper inter-heating, flashing, multi-pressure stripping, electrochemically mediated regeneration, computational tools for system integration. The benefits in terms of efficiency improvements will need to be weighed against possible increases in complexity and capital costs. Both improved solvents and new processes may require heat at different temperatures, pressures or steam volumes. Thus, upgrading a CCS-equipped power plant to use an improved solvent may require modification to the integrated CO_2 capture and power plant system. Further work is required to understand trade-offs between static optimisation and future-proofing of concepts.

Integrating CO_2 capture in alternative power generation cycles

Investing in new CCS-equipped power generation in the 2DS is a very different proposition from investing in a CCS retrofit. A fossil fuel power plant equipped with CCS from the outset could adopt higher-cost combustion and power generation technologies if these are more than offset by lower CO_2 capture costs. The aim is therefore to optimise both power generation and CO_2 capture, resulting in the lowest cost per megawatt hour. This is the approach of pre-combustion and oxy-fuel combustion. In oxy-fuel combustion, the expense of pure oxygen is offset by lower CO_2 capture costs at the end of the process. Tighter integration of CO_2 capture with power generation systems may more easily enable the capital cost reductions implied by the 2DS learning rate (Figure 5.2).

In addition, to be competitive in a decarbonising electricity market (with high penetration of variable renewables and low marginal costs), technologies are likely to need to be:

- technically flexible, to follow load, balance variable generation and provide network services such as frequency response
- economically flexible by reducing capital costs, generating at times of high prices and minimising the efficiency penalty of part-load operation.

Several ways of meeting these needs have been proposed that involve redesigning the traditional power generation cycle so that CO_2 capture is integrated into the power generation process, reducing the parasitic heat demand for solvent regeneration. The efficiencies of such redesigned plants, including inherent CO_2 separation, could be closer to those of unabated power plants, offering an advantage in the search for sweet spots. Compared with post-combustion capture, technologies that offer higher overall efficiency, flexibility or modularity might be highly valuable in certain electricity systems even if specific capital costs are higher.

Technology innovation for oxy-fuel combustion

In oxy-fuel combustion processes, the fuel is burnt in oxygen rather than air. The resulting flue gas is primarily CO_2 and water. Some of the flue gas is recycled to the combustion process to maintain the proper ratio of fuel to oxygen, and the remainder is dehydrated and compressed for transport and eventual storage. Oxy-fuel combustion has been successfully operated at scales of 30 MW_e.

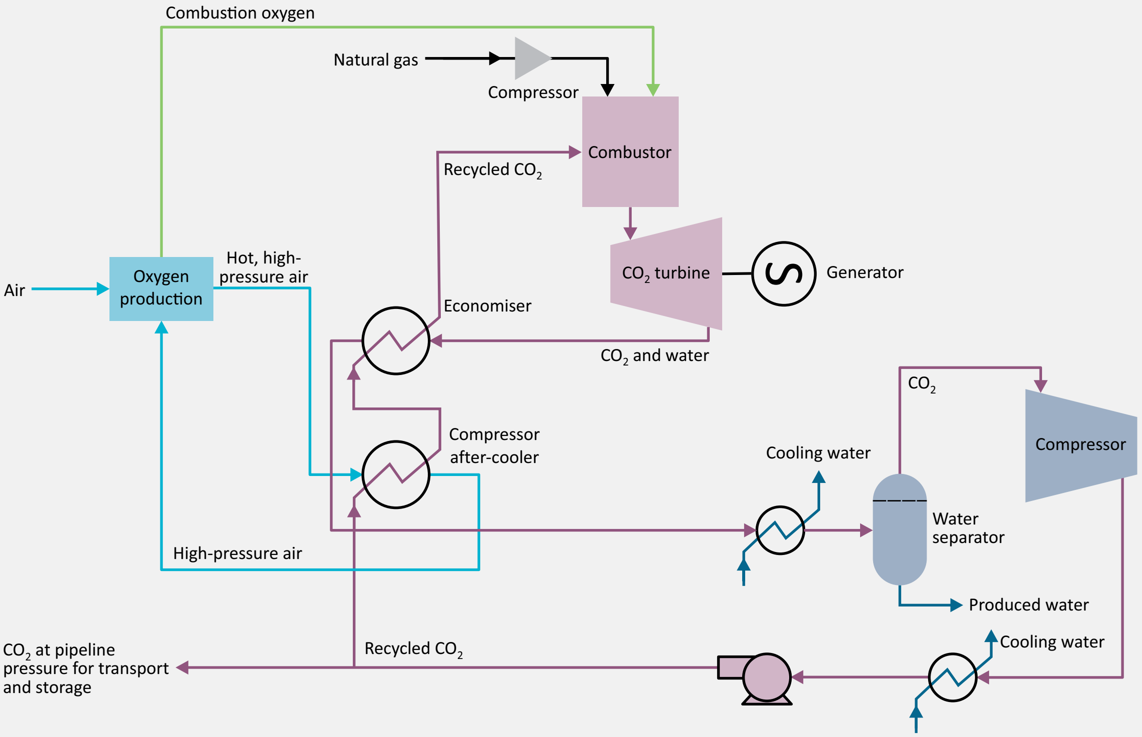
While this process appears simple, large volumes of oxygen are needed for combustion, which requires a large and costly air separation unit (ASU). The potential for improvements in ASU technology and integration of the ASU into the plant will benefit most oxy-fuel technologies. Large quantities of oxygen are also needed in many non-power generation applications (e.g. gasification, steel making), so there are substantial market incentives for innovation.

Oxy-combustion turbine-based cycles

In oxy-combustion turbine-based cycles, a gaseous fuel is combusted in an atmosphere of oxygen and recycled flue gases, and the combustion products – a mixture of CO_2 and water – are expanded through a modified turbine, which drives a generator. Depending on their design, they may or may not include a “bottoming” cycle that extracts further energy from the working fluid. The use of CO_2-water mixtures as a working fluid eliminates much of the expense of CO_2 separation processes. While many cycles have been proposed, few have reached the pilot stage. Two that have been demonstrated in field trials are the Clean Energy Systems (CES) Water Cycle (Aldous et al., 2013) and the NetPower Allam Cycle (Allam et al., 2013). In the CES Water Cycle, the working fluid is 80% water, while in the Allam Cycle, the working fluid is 80% CO_2 (Figure 5.8). Both cycles benefit from being net producers of water, and promise efficiencies comparable with CCGTs (without CO_2 capture) at similar capital costs. In late 2014, NetPower and its partners decided to invest in a 50 MW_{th} demonstration plant in the United States, which they expect will enter operation in 2017.

The main drawback of these and other oxy-fuel cycles is that they require large amounts of high purity oxygen and advances in materials and turbomachinery design to achieve promised efficiencies. As with gasification and more conventional oxy-combustion-based processes, they will strongly benefit from increases in the efficiency of oxygen production. Leading examples of oxy-combustion turbine-based cycles are likely to be a decade away from being commercially available.

Figure 5.8 The Allam Cycle, one example of an oxy-combustion turbine-based cycle



Source: Allam, R. (2013), "High efficiency and low cost of electricity generation from fossil fuels while eliminating atmospheric emissions, including carbon dioxide", *Energy Procedia*, Vol. 37/0, Elsevier, Amsterdam, pp. 1135-1149.

Key point *Oxy-combustion turbine-based cycles are less complex than some other oxy-fuel combustion and pre-combustion processes.*

Pressurised oxy-coal combustion-based systems

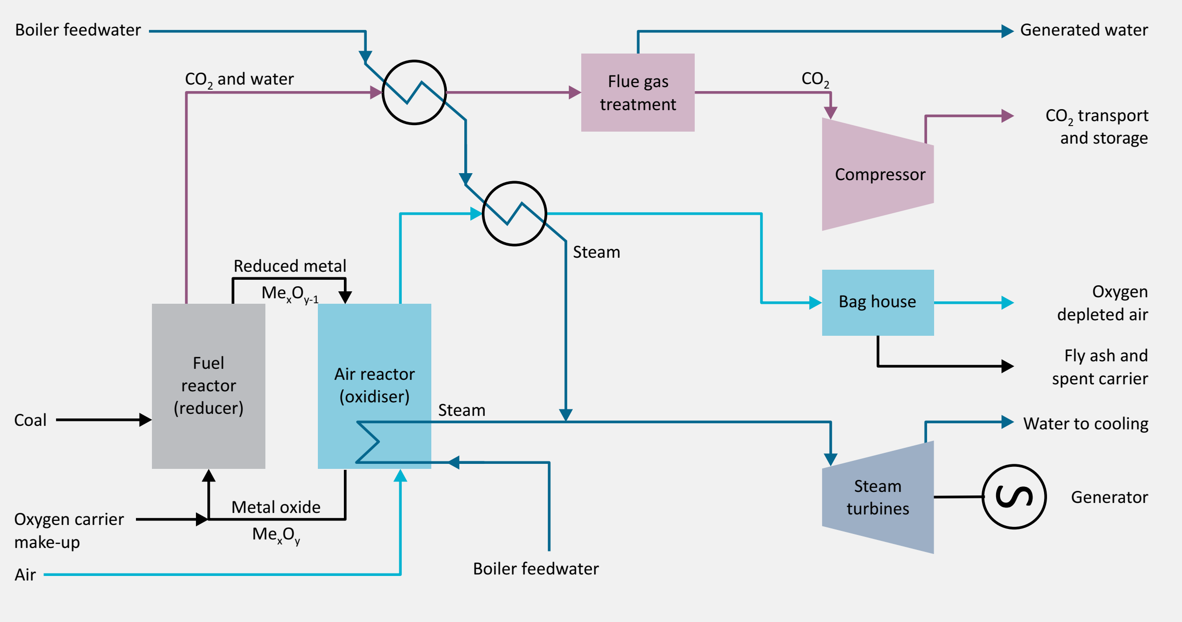
Pressurised oxy-coal-based systems are generally based on modification of a fluidised bed boiler to operate at higher pressures in an oxy-combustion mode. As in a conventional coal-fired plant, the majority of the electricity generated from combustion is extracted through a conventional Rankin (i.e. steam) cycle, but efficiencies are expected to surpass those of comparable pulverised coal plants with CO_2 capture (Hong et al., 2009).

Pressurised oxy-coal systems with CO_2 capture are at an early stage of development and the subject of significant research. Some components are commercially available. Others, notably the pressurised fluidised bed boiler, have been tested at small scales in the United States, but pilot plants have not yet been developed. With continued support, commercial pressurised oxy-coal plants could become available in the late 2020s or 2030s.

Chemical looping combustion-based systems

Chemical looping combustion (CLC) generally refers to a family of processes in which a solid oxygen carrier is reduced in the presence of a solid or gaseous feedstock, and regenerated through oxidisation in the presence of oxygen. CLC and closely related processes (e.g. integrated gasification-CLC and chemical looping with oxygen uncoupling) are the most straightforward candidates for power generation from gaseous or solid fuels.[19] In most designs of CLC-based power plants, the oxygen carrier would be circulated between a fuel reactor, the exhaust from which is a mixture of CO_2 and water, and an air reactor, from which the exhaust is oxygen-depleted air (Figure 5.9). In this case, neither CO_2 separation nor a dedicated air separation plant is required, making this process attractive from efficiency and, potentially, cost standpoints.

Figure 5.9 **Chemical looping combustion-based power plant**



Key point *Neither CO_2 nor air separation processes are needed for CLC-based power plants.*

The first CLC process for power generation was proposed in the 1980s as a means to improve efficiency, following introduction of the basic concept in 1951 (Lewis, Gilliland and Sweeney, 1951; Richter and Knoche, 1983). The pace of development increased sharply in the early 2000s when it was realised that CLC-based power plants could lead to low-cost CO_2 capture. The principles behind CLC-based systems have been developed through several thousand hours of operation of at least a dozen laboratory- and bench-scale units in China, Europe, Korea and the United States (Adanez et al., 2012; Lyngfelt, 2014). The largest prototype is around 3 MW_{th} in size and has been developed by Alstom with US DOE funding.

The challenges facing development of CLC for solid fuels are greater than those for gaseous fuels such as natural gas and syngas. Solid fuels must be gasified in the fuel reactor before being combusted, or an oxygen carrier must be chosen that spontaneously liberates oxygen at the conditions in the fuel reactor. In addition, ash remaining after combustion of solid fuels must be removed from the system, which results in losses of the oxygen carrier. So developing CLC-based processes requires identification of reactive and durable, low-cost

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[19] Chemical looping processes can also be designed for combustion of fuel as part of a steam generating process, as in a power plant, or for producing hydrogen.

oxygen carriers optimal for use with solid fuels; designs to improve conversion of solid fuels; and scaling up the reactors and solids handling systems. With continued support, commercial CLC-based systems could become available in the late 2020s or 2030s.

Continuing progress in pre-combustion technologies

Pre-combustion capture is similar to post-combustion capture insofar as CO_2 is removed from a gas stream. In pre-combustion capture, however, the CO_2 is contained in a high-pressure fuel gas that consists primarily of hydrogen, nitrogen (the amount of which depends on the gasification or reforming technology) and water. Because the partial pressure of the CO_2 is higher than that in flue gas in post-combustion capture, a physical rather than chemical solvent is generally used. After removal of CO_2, the fuel gas is burnt in a CCGT modified for the hydrogen-rich fuel, to produce electricity. As in post-combustion capture, the captured CO_2 is dehydrated and compressed for transport to a storage site.

The principal challenges faced by pre-combustion processes are the high cost of integrated gasification combined-cycle (IGCC) plants without CO_2 capture and, relative to pulverised coal steam cycles, the immature state of IGCC technology. While IGCC plants could offer low LCOE with CCS, they have a high cost of CO_2 avoided when compared with conventional unabated coal plants and thus are rare. The first full-scale IGCC with pre-combustion capture, the 582 MW_e Kemper plant, is being built in Mississippi and is expected to enter operation in 2016. This plant has faced significant cost overruns and delays in construction, however, resulting in part from the use of a new gasifier technology for low-rank coal.

Considerable research is being undertaken into technologies related to IGCC, such as hot gas clean-up, improved turbines and ASU technologies, which are needed for IGCC as well as oxy-fuel plants. Lessons from research and future deployment of IGCC will help to improve the economic case for pre-combustion capture.

The need for innovation to manage CO_2 storage costs

Storing captured CO_2 involves injecting it into a carefully selected geological formation, usually more than 1 km below the surface, where the CO_2 is retained by natural trapping mechanisms. The surrounding storage site is monitored to demonstrate retention. Most CO_2 storage technologies are adapted from those developed for hydrocarbon exploration and production.[20] So innovation in the oil and gas sector, which is a major area of technology development globally,[21] will likely also benefit CO_2 storage, helping to reduce costs.

The oil and gas sector has over four decades of experience with handling and injecting CO_2 using wells designed specifically for this purpose. Around 100 $MtCO_2$/yr are used for EOR. Yet climate policies in all but a couple of countries have yet to make an economic case for CO_2 storage that compensates for the up-front costs of exploration and storage site development, let alone the costs of capturing CO_2.

This section looks at the nature of CO_2 storage, the cost components and the scope for reducing costs via technological and regulatory innovation. Such cost reductions will be essential to combat the inflationary pressures of geological resource depletion and competition between CO_2 storage and the oil and gas sector for skills and materials.

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[20] Most of the elements of CO_2 storage – exploration, appraisal, well drilling and operation, completion – are integral components of oil and gas production. Operators routinely use the technologies and understand the technical risks.

[21] Annual R&D and exploration investments currently reach approximately USD 9 billion for oil and USD 100 billion for gas (EU, 2013; Barclays, 2013).

Storage cost components

Storage costs fall into five categories: exploration, development, injection, monitoring and closure. These categories roughly correspond to the phases of a storage project, but the mapping is not one-to-one, as monitoring usually begins before injection and continues after it.

- **Exploration** includes the costs of collecting data – gathering existing data and undertaking new measurements – and of analysing data to select the most suitable site. Exploration costs are influenced by the time and uncertainty involved in finding suitable storage resources.
- **Development** includes costs associated with the design of injection schemes and surface equipment, as well as drilling and completion of injection and monitoring wells (some of which may have been drilled during the exploration phase), installation of flow lines and other permanent surface equipment, and remediation of existing wells.
- **Injection** includes the costs of day-to-day operations at the storage site, covering personnel, supplies and energy for any compression that may be required. This category would also include the operational costs of pressure management schemes (e.g. production of formation water), operational measurements, and routine maintenance.
- **Closure** involves costs of wellbore plugging, decommissioning of surface equipment and, when necessary, removal.
- **Monitoring** includes the costs of establishing a pre-injection baseline for the site, surveillance of the site and injected CO_2 through geophysical methods as well as sampling of reservoir fluids, and similar but less frequent activities following injection until site closure.

While the distribution of costs can be very heterogeneous, exploration and development costs, which are incurred before injection begins, can represent as much as half of total undiscounted storage costs (Figure 5.10). This means that considerable expenditure must be approved without certain knowledge of the revenue to be expected, if any. Significant cost growth and production shortfalls are common in the oil and gas sector, even after the start of site development (Merrow, 2011). So the pre-injection period carries a high risk, which needs to be compensated for through contingency costs or high rewards for successful development. As in the oil and gas sector, CCS (or CO_2 storage) business models will need similar rewards. Reducing exploration and development costs is vital, and a good focus for innovation in both technology and policy.[22]

The natural inflation of CO_2 storage costs

Experience in the oil and gas sector shows that both technical and regulatory innovations will be required to offset CO_2 storage cost increases due to progressive degradation of the storage resource over time; competition for goods and services between CO_2 storage and the hydrocarbon sector; and a potential lack of political and public acceptance.

Geological storage capacity is finite and non-renewable. The distribution of global CO_2 storage resources is likely to be similar to that of oil and gas: few very large contiguous sites but a larger number of smaller, physically distinct sites (GHG IA, 2011). Storage sites vary in terms of their geological properties and, consequently, costs per tonne of CO_2 stored. Costs are influenced by factors such as depth, reservoir quality and

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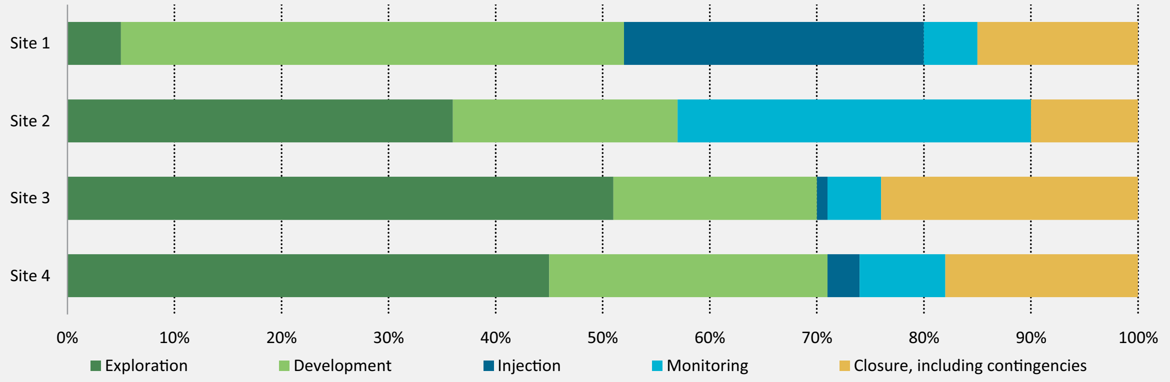
[22] Note that some situations may justify an increase in absolute up-front costs if they proportionally raise the cumulative stored CO_2 for a site and thus reduce unit costs.

structure, number of wells required, uncertainty about the precise geology, need for active pressure management,[23] whether the injection site is onshore or offshore, and regulatory requirements. This quality varies both within and between "plays" – groups of potential sites in the same region with the same geology (a term borrowed from oil and gas exploration).[24]

Figure 5.10 Proportion of total CO_2 storage costs associated with project phase for four studied European storage sites



Notes: Sites 1, 3 and 4 are offshore saline aquifers. Site 2 is an onshore saline aquifer. Site 1 would require pressure management during the injection phase. Detailed prior knowledge is available only for Site 1. The storage quantities assumed for the estimations are relatively small, 1 $MtCO_2$/yr to 5 $MtCO_2$/yr. Costs are equivalent storage costs (ESCs).
Source: Gruson et al. (2014), "Techno-economic assessment of four CO_2 storage sites", *Oil & Gas Science and Technology*, In Press, IFP Energies nouvelles, Rueil-Malmaison, France.

Key point *Storage costs are distributed unevenly between project phases and differ between projects. Exploration and development can represent half of total undiscounted storage costs.*

The first CCS projects may select storage sites based on limited local knowledge and availability. As CO_2 storage develops as a business, however, it is likely to follow a trajectory that mirrors that of oil and gas and, to a large extent, wind power (US EIA, 2013): first finding and developing the highest quality sites, which deliver the best opportunity for financial returns, and then moving to the more expensive sites. The key finding of many studies is that there is tremendous variability in the cost of storage in saline aquifers. Unit costs[25] have been estimated to range from less than USD 1/tCO_2 to over USD 100/tCO_2 for the United States – not including the cost of pore space acquisition from private rights holders (Herzog et al., 2005; McCoy and Rubin, 2009; Kobos et al., 2011; Eccles et al., 2012).

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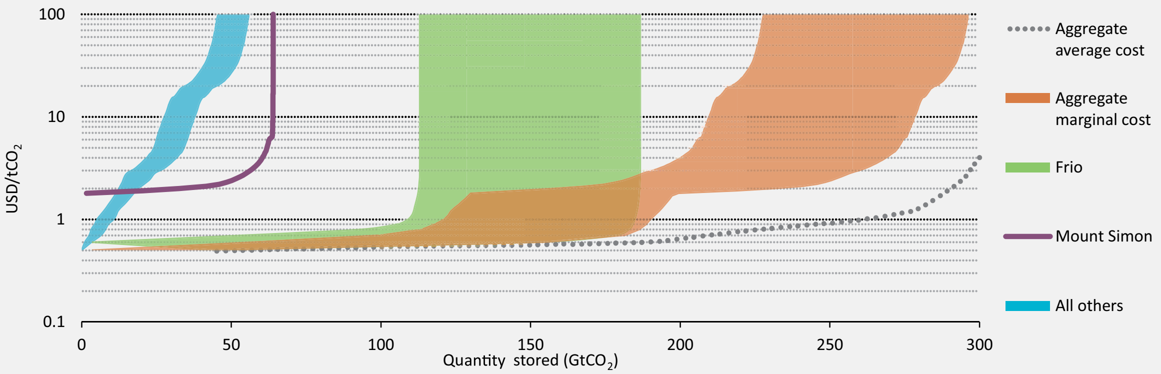
[23] Regardless of the quality of a storage site, its performance will diminish as it is filled, largely because pore pressure increases can reduce injection rates or require pressure management.

[24] Engineering studies of CO_2 storage projects have shown that achieving similar performance from two different onshore storage plays in the same country could require a twenty-fold difference in the number of injection wells (13 wells versus 254 wells) (Garnett, Grieg and Oettinger, 2013). Offshore plays have higher capital and operating costs, resulting in unit costs two to three times higher than onshore (ZEP, 2011). The quality of the geological formation and the depth of the site will also have a significant bearing on capital and operating costs.

[25] Unit cost is estimated to be the break-even price per tonne of CO_2 stored over the life of a project. This is calculated as the ESC whereby the discounted storage cash flows are divided by the discounted quantities of CO_2 injected.

CO_2 storage costs in the United States could rise by an order of magnitude as additional storage resources are exploited (Dooley et al., 2004; Eccles et al., 2012).[26] For onshore storage, however, most papers suggest that a tremendous amount of capacity should be accessible at costs of a few US dollars per tonne in the United States (Figure 5.11). Using these figures, storage costs represent around 5% of the costs of power generation with CCS in the United States in 2020. However, in a region where storage costs were as high as USD 25/tCO_2, for example offshore saline aquifer storage in Europe, this could rise to one-third of the costs of power generation with CCS. Innovation can mitigate the natural tendency for costs to rise.

Figure 5.11 **Estimated marginal and average injection costs for CO_2 storage in the United States**



Notes: Frio (Texas) and Mount Simon (Illinois) are sandstone formations in the United States. Costs are calculated on the basis of a project storing 10 $MtCO_2$/yr over a period of 20 years. Solid areas represent the marginal cost range of storage for the next unit of storage capacity while the dashed line represents the average cost for all CO_2 stored up to the given quantity indicated on the horizontal axis.
Source: Eccles et al. (2012), "The impact of geologic variability on capacity and cost estimates for storing CO_2 in deep-saline aquifers", *Energy Economics*, Vol. 34/5, Elsevier, Amsterdam, pp. 1569-1579.

Key point *CO_2 storage costs vary depending on geological factors, but supply curves indicate technical availability of sufficient resources at relatively low costs.*

In addition to the natural tendency for resource costs to increase, there will be cases where the best CO_2 sites are unavailable due to a lack of local political and public acceptance. Furthermore, some sites may be placed off-limits if there are conflicting priorities for resource exploitation, for example with geothermal energy, oil and gas, or other minerals extraction (GHG IA, 2013). These factors could mean that more expensive sites would have to be used before others, accelerating the increase in storage costs.[27]

CO_2 storage costs could also be pushed up by competition for skilled personnel, goods and services between CO_2 storage operations, and oil and gas exploration and production. Even in the 2DS, oil and gas demand grows in the near to medium term. This could lead to further cost inflation for CO_2 storage projects, which seem unlikely to be able to outbid oil and gas projects. Depending on the outcomes of early projects, regulatory requirements

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[26] For comparison, recent large oilfield developments report a range of break-even costs from USD 30 per barrel to USD 120 per barrel (Goldman Sachs, 2011). This reflects development in more technically challenging regions.

[27] In the near term, the inverse may also apply. If early CCS projects are highly successful, public acceptance may rise and additional storage resources may become available as a result.

for monitoring as well as the costs imposed by liability management mechanisms (e.g. insurance, bonds or government funds) could also increase.

Nevertheless, experience in the oil and gas sector shows that there are opportunities for innovation and policy to counteract these factors (Table 5.4). Improvements in technology have allowed resources that were otherwise uneconomic or unreachable (e.g. high-pressure and high-temperature plays, shale gas) to be converted to reserves (Simpson, 1999; Managi et al., 2005). In addition, as the business of CO_2 storage grows, the costs of finding and proving storage resources can be spread over a larger number of projects.

Table 5.4 Factors that will raise and factors that can lower CO_2 storage costs

Factors that will raise CO_2 storage costs over time	Factors that can help lower storage costs
Exploitation of the lowest-cost storage resources first.	Technological innovation for reducing exploration and development costs.
Inflationary pressures in the oil and gas sector and competition for skills, goods and services.	Transfer of skills and services from oil and gas sector to CO_2 storage over time.
Limited access to the best storage sites, for example due to lack of public approval.	More efficient regulation.

Relevant technological innovation for CO_2 storage is well under way

Whereas today's CO_2 capture projects are often considered to be first of a kind, most of the necessary technologies for CO_2 storage have already been well developed in the oil and gas sector. This may reduce the potential for technological breakthroughs that radically reduce costs, but it also means that CO_2 storage will benefit from incremental advances that can be transferred between the sectors. For example, it is estimated that in the 1970s, drilling and completion times for the development of oil fields fell from 80 days to 40 (Ikoku, 1978). Cumulative experience in drilling wells in the oil, gas, geothermal and other sectors will cross over to CO_2 storage.

Beneficial innovations will help reduce exploration and development capital expenditure in at least three ways:

- by reducing the costs of finding an additional unit of CO_2 storage resource[28]
- by reducing the cost of and time for proving and developing CO_2 storage resources
- by expanding the accessible reserves by reducing the costs and risks of exploring in hostile environments.

Examples of improvements that have had these effects in the oil and gas sector are discussed below.

Reducing finding costs

Reducing the costs of finding profitable plays is a notable way in which innovation can mitigate the effects of resource degradation. In the oil and gas sector, technologies

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[28] The aim is not to minimise finding costs per se, but to maximise the value of the information obtained and minimise overall costs of storage by selecting the best geological option for development (or walking away before additional costs are sunk into the project).

developed for this purpose are estimated to have increased the exploratory success rate in the United States onshore by around 7% between 1986 and 1998 (Forbes and Zampelli, 2002). Offshore, cumulative cost savings from technical change in the United States were estimated at 18% in 1994, more than offsetting a 12% increase due to depletion effects (Fagan, 1997).

The development of 3D seismic technology played a role in preventing finding costs from increasing in line with depletion effects (Cuddington and Moss, 2001). From the late 1980s, 3D seismic technology increased the success rate of exploration wells from 30% to 50% (Bohi, 1999). The average 3D well brought in 14% more reserves than wells based on 2D seismic exploration.

Many innovations that improved costs, and therefore competitiveness, in the oil and gas sector were at least partly publicly funded. For example, in the late 1980s the US DOE helped to improve seismic imaging by granting the oil and gas sector access to more computing power, by developing algorithms and by investing in a multi-station borehole seismic receiver (Singer, 2014). Thus, the US government took on some of the risks that were not prioritised by the private sector, something that is recommended for CO_2 storage technologies, rather than fossil fuel production, today.

Reducing costs of proving and developing storage resources

Once a storage resource has been located, it is necessary to prove that it has the appropriate geological attributes and that the behaviour of CO_2 in the storage formation can be predicted with high confidence. Technologies that enable better mapping of the subsurface and greater confidence in its performance will be important tools for reducing up-front risk. In addition, developments in reservoir simulation (e.g. coupled flow and geomechanical models) could have significant benefits for both CO_2 storage and oil and gas. The desired impact is to minimise the time it takes to prove a storage site to the satisfaction of investors, regulators and other stakeholders, while increasing the success rate. This in turn reduces labour and leasing costs, and other costs associated with delays to development.

Developing a proven resource involves drilling and completing wells, installing surface infrastructure and identifying (and potentially reworking) previously abandoned wells. Technology to identify and evaluate the integrity of old, abandoned wells could be highly valuable for CO_2 storage. In the oil and gas sector, break-even costs and risks for unconventional resources have been reduced as a result of improvements in horizontal, multi-stage hydraulic fracturing and field specific operational learning. Other technologies that have contributed innovations in this sector include polycrystalline diamond compact drill bits, deep drilling, floating drilling and underwater wellheads.

Expanding the accessible storage resource

In the longer term, technologies that increase the depth or surface area that can be explored or that make low-grade resources exploitable may open up new storage resources. The desired impacts of technical innovation in this area will include access to high-quality geological formations, lower CO_2 transport distances and limited long-term unit cost projections. In the oil and gas sector, technologies have enabled operations in more hostile or difficult environments including subsea wells, offshore platforms equipped for hostile environments, tension leg platforms, horizontal drilling and hydraulic fracturing.

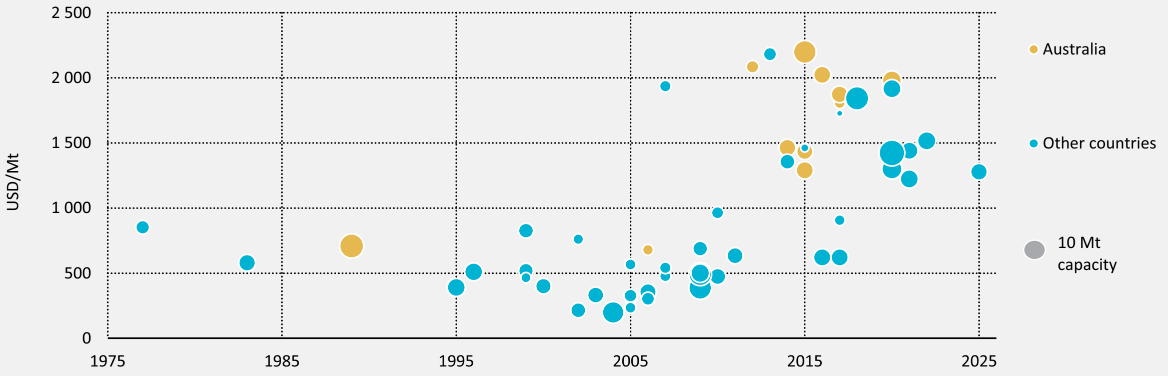
Avoiding cost inflation by transferring oil and gas skills to CO_2 storage

In the 2DS, CO_2 storage will compete with oil and gas exploration for access to the same skills, goods and services. This poses a problem for CO_2 storage, because it seems likely that oil and gas projects will be able to outbid CO_2 storage projects as long as oil and gas are highly valued and widely used.

Looking at the 2DS, both CO_2 storage and oil and gas production are major activities in the 2050 time frame. CO_2 storage increases from 50 $MtCO_2$/yr in 2020 to 1 490 $MtCO_2$/yr in 2030 and 6 320 $MtCO_2$/yr in 2050. World oil supply peaks at 4 220 million tonnes of oil equivalent per year (Mtoe/yr) before 2020 and then falls to 1972 levels (2 630 Mtoe/yr) by 2050. World natural gas supply peaks at 3 040 million tonnes per year (Mt/yr) by 2035 and then falls to 2010 levels (2 560 Mt/yr) by 2050. Reduced demand for oil and gas may therefore alleviate inflationary cost pressures and allow a staged transfer of skills and resources from one sector to another. This may extend to the conversion of depleted hydrocarbon reservoirs to CO_2 storage. However, this will probably be offset by new oil and gas plays being more labour- and material-intensive.

Significant barriers can exist to the flow of skilled labour and materials, driving up prices in regions where megaprojects are being developed. This has been cited as one of the factors responsible for increases in capital costs for LNG projects, particularly in Australia, where two-thirds of global investment in LNG has occurred (IEA, 2014c) (Figure 5.12). Because several projects are being built simultaneously, there has been strong upward pressure on costs because local supply chain issues have been outpacing learning effects. Moves to more remote locations, greenfield sites (without infrastructure connections), technical complexity and appreciation of the Australian dollar have also contributed. Competition among technology suppliers helped reduce capital costs of early LNG projects (Greaker and Sagen, 2004).

Figure 5.12 Increase in capital costs of LNG liquefaction plants



Note: Areas are proportional to total plant capacity.

Sources: IEA (2014b), *World Energy Outlook Special Report: World Energy Investment Outlook*, OECD/IEA, Paris; Songhurst, B. (2014), "LNG Plant Cost Escalation", *Oxford Institute for Energy Studies (OIES) Paper NG 83*, OIES, Oxford, United Kingdom; Wood Mackenzie (2014), *Wood Mackenzie database*, Midlothian, United Kingdom.

Key point *In the short term, technology costs can increase as deployment rises due to non-technical factors, such as personnel shortages and competition for materials, that can be managed by policy.*

Policy can help to control such cost inflation by increasing the supply of skilled personnel, raising the attractiveness of activities with a public-good dimension and managing strategic physical resources. Furthermore, governments can take advantage of the synergies between oil and gas production and CO_2 storage by maximising the climate benefits of EOR and managing the transformation of depleted hydrocarbon reservoirs into CO_2 storage sites.

Regulatory measures to lower CO_2 storage costs and risks

As resource holders, licensing authorities and tax collectors, governments have a critical cost-limiting role. There are several actions that regulators can take to help minimise costs, some of which could require innovative approaches to the role of the public sector. Predominantly, this will be in ensuring that the highest quality and largest storage sites are de-risked and available for licensing. Three areas for regulatory attention are discussed in this section:

- reducing exploration costs and targeted acreage release
- ensuring access to infrastructure and resources
- managing regulatory complexity and credibility.

Reducing exploration costs and targeted acreage release

Given the risks inherent in private investment in exploration, governments could accept a high share of the costs of pre-competitive drilling, testing and gathering data, in line with national mitigation aims and scale. The resulting information would also be valuable for policy planning and could be viewed as an investment in the resilience of a region's industry under a low-carbon scenario (Friedmann et al., 2006). Favourable tax treatment for storage exploration and development – for example, through credits or other relief on early losses or accelerated depreciation – could be considered. These costs might be recouped through the tax system, through licensing arrangements or by taking an interest in storage projects.

Using targeted release strategies, the best and most scalable resources can be promoted for development first. This can help manage the near-term risk that CCS project proponents may seek only sites that are sufficient for their projects. What is economically best for individual projects may not be optimal for overall resource exploitation over the 2DS time frame.

Developing large or lower-cost fields first reduces the break-even costs of nearby smaller, lower quality fields and plays. In the near term, this function might be fulfilled by EOR projects (GHG IA, 2009) or enhanced water recovery. This is a result of learning by doing within a particular CO_2 storage play, something that has been observed for unconventional oil and gas (Burruss, 2009; Guo et al., 2012).

Ensuring access to infrastructure and resources

Governments have a role to play in regulating access to shared CO_2 transport and storage infrastructure, which is a feature of cost-optimal deployment scenarios. As storage benefits from scale, the emergence of hubs to which several sites are connected will allow development costs to be shared across large volumes of CO_2 stored. For example, optimising the scale up of transport and storage infrastructure could represent the largest impact on CCS cost reductions in the near to medium term in the United Kingdom (UK Carbon Capture and Storage Cost Reduction Task Force, 2013).

By keeping the public fully informed of risks and benefits, governments can also lower the risk of public opposition that could increase storage costs by making lower-cost resources inaccessible.

Managing regulatory complexity and credibility

Neighbouring, overlapping or competing resource developments, such as oil and gas production, mining, agriculture and geothermal energy, can create regulatory complexity and stakeholder sensitivities. In addition, cost increases can arise from a lack of regulatory credibility due to uncertainty in the regulatory environment that leads to delayed investments in innovation, long lead times for permits, complex designs or a lack of standardisation (AGPC, 2009; Bosetti and Victor, 2011; Godec and Biglarbigi, 1991; MacKerron, 1992).

Some early large-scale CO_2 storage projects have encountered unforeseen delays because environmental regulators were not familiar with permitting processes, including permitting of similar types of projects in the oil and gas sector, and because the performance requirements of regulatory frameworks for storage are demanding. For example, almost two years passed between the application for and issuance of the first geological storage permits in the United States. Prolonging the time it takes to bring a project to operation defers the start of revenue flows and, compared with other capital expenditure elements, can disproportionately raise investment risk and therefore overall costs. As more projects are assessed for permits, lessons learned by both regulators and applicants should reduce the time between permit applications and decisions. Sharing experience among regulatory bodies within, and among, jurisdictions will help this process.

Recommended actions for the near term

Governments should implement policies that place a cost on emissions or set appropriate emissions intensity standards and ensure permanent CO_2 storage. CO_2 capture, transport and storage technologies are already commercially viable, but only where the necessary policy and market conditions align. This includes places where governments have moved to reduce venting of CO_2 after natural gas processing and where governments have supported innovation by covering additional costs of key technologies (e.g. in bioethanol or hydrogen production applications). In these sectors, especially if coupled with the revenues from CO_2-EOR, large-scale CCS could be possible today at relatively low CO_2 abatement costs.

Experience with large-scale integrated CCS needs to be increased by creating the conditions for investments in a steady pipeline of projects. At present, the low level of experience is an impediment to innovation and accurate cost estimation. Without experience, CCS mitigation costs and risks do not decline; without clear knowledge of costs and risks, governments are unwilling to commit to strong climate policies that would incentivise CCS; long-term signals are not sent to investors to prepare the ground for CCS deployment; experience is acquired only slowly. This vicious cycle is a particular problem for CO_2 storage as it limits the motivation for exploration and development of storage sites, an activity that must be undertaken well in advance of CCS commercialisation.

Governments can create the conditions under which CCS technologies can flourish in an increasing number of sweet spots. This will stimulate a virtuous cycle of commercial experience, cost reduction and new commercial opportunities. It should also increase public support, which could be pivotal for CCS deployment in some regions and may rest on assertive communication by governments. Policy makers need an understanding of technologies accumulated through commercial experience in sustainable niche applications before scale up to more competitive markets and diverse social pressures.

In post-combustion capture for power plants, more large-scale projects supported by partnerships between public and private organisations are needed. CO_2 separation energies have been halved since mature technologies originally developed for the food and chemicals sectors were first adapted to power generation, a mass-market, low-cost application. But the learning rates in the 2DS could also require the availability of novel approaches to CO_2 capture to enable widespread retrofitting of coal-fired power plants.

At the same time, power generation technologies that more fundamentally integrate CO_2 capture must evolve to meet the commercial demands of the electricity sector and, potentially, government performance targets for CCS. This need should help guide government R&D investments, and portfolio approaches are recommended to maintain a diverse set of technology options and accelerate innovation. Balanced portfolios should include technologies representing both lower-risk, incremental improvements and higher-risk, more profound improvements.

For CO_2 storage, governments can reduce the significant up-front risks associated with CO_2 storage exploration in several ways, including targeted acreage release, management of regulatory complexity, and management of competition with the oil and gas sector for skills and resources. Investments in CO_2 capture in most regions will critically depend on the availability of cost-effective storage businesses. To this end, governments should co-invest in early projects that deliver vital learning by storing and monitoring CO_2, especially in saline aquifers. While some CCS projects have secured public and private investments totalling over USD 1 billion,[29] it is unclear whether such funding will be available for additional projects in the near term. Governments can consider sectors where public investments in CCS learning might be made at lower capital costs while climate policies to support commercial-scale CCS are strengthened. For example, for around USD 100 million, a project storing over 100 kilotonnes of CO_2 per year ($ktCO_2$/yr) might be feasible in all but the cement and electricity sectors (Table 5.5).

Table 5.5 “Bite-sized” CCS: What scale of projects might be undertaken for different investment costs

Capital expenditure (USD million)	Indicative amount of CO_2 that could be stored per year ($ktCO_2$)				
	Gas processing	Bioethanol	Chemicals (methanol, ammonia) and refining (hydrogen)	Cement	Coal-fired electricity
50	200	< 100	< 100	x	x
100	600	20	100	< 100	< 100
200	1 500	700	300	200	150
500	4 000*	2 000*	1 000	850	500

Notes: x = not applicable. IEA analysis based on published figures for large-scale projects or state-of-the-art capture technologies that do not assume reengineering of the base plant. Projects are assumed to be full chain CCS projects using onshore saline aquifer storage and pipeline transport distances less than 100 km. Revenue from CO_2 sales or climate policy instruments is not accounted for. Approximate costs assume location in OECD country; projects in, for example, China, could have considerably less capital expenditure. Annual operational expenditure will vary depending on design and revenue streams but is likely to be around USD 10 000 per tonne of CO_2 for gas processing and several times higher for more complex CO_2 capture processes.
*Exceeds the size of most industrial facilities in this sector.

Key point: *“Bite-sized” opportunities for CCS learning-by-doing, including CO_2 storage, are mostly related processes where CO_2 separation is inherent and almost pure CO_2 is currently vented to the atmosphere.*

Technology deployment gathers momentum only when concerted effort is made to align it closely with the preferences of society and with decision makers’ visions of the future. “Sweet spots” can require public approval for the technology in the relevant sectors and

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[29] Much of this funding arose from time-limited economic stimulus packages.

locations, which policy makers can work to identify and foster. Governments should also establish effective networks for creation and exchange of knowledge between researchers and practitioners. The US Regional Partnerships are identified as having contributed to such a network in the United States (Van Alphen et al., 2009) and research networks in other countries[30] are likely to fulfil a similar role.

Over time, as experience rises and costs decline, CCS will become commercial in additional sectors such as power generation, steel and cement. CCS can benefit from knowledge exchange among the different sectors, particularly in CO_2 capture, and also from the sharing of transport and storage infrastructure. Because CCS internalises CO_2 costs, providing a public good, each new project will be a partnership between the public and private sectors and each will inform the next project. This process can be accelerated in the period up to 2030 through strong government commitment to deep emissions reductions throughout the economy.

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[30] For example, the UK CCS Research Centre, the Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) in Australia, CO_2 Afvang, Transport en Opslag (CATO) in the Netherlands, the EU European Energy Research Alliance (EERA) and CO_2 GeoNet, and in Canada, Canadian Oil Sands Innovation Alliance (COSIA).

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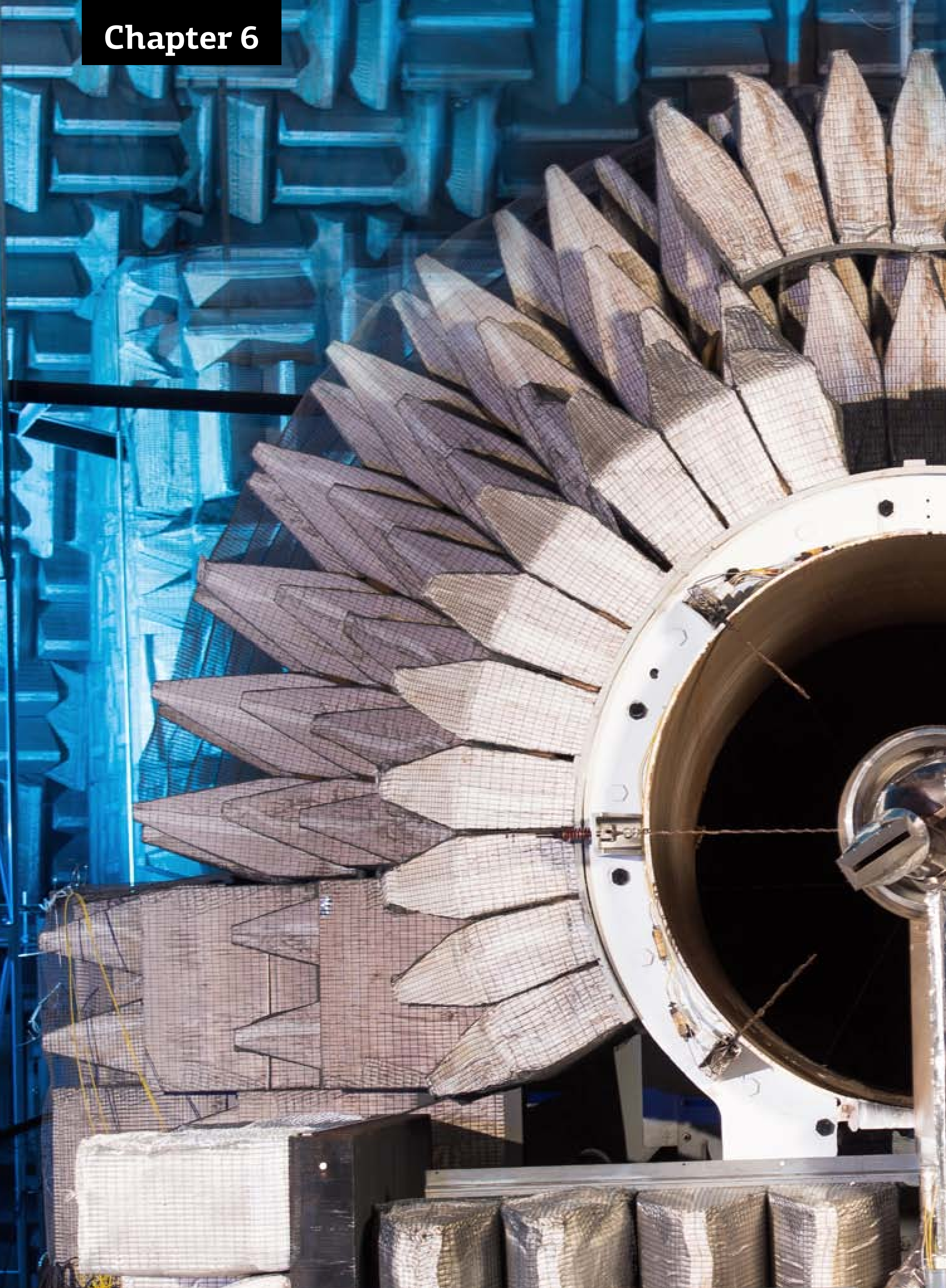
Chapter 6



Global Innovation for More Sustainable Industry

Progress on low-carbon industrial innovation over the next decade is crucial to achieve the 2°C Scenario (2DS) carbon dioxide (CO_2) emissions reduction. Economic and policy uncertainty, and the need to manage risk and maintain competitive advantage, create substantial challenges. By aligning strategic goals and establishing co-operative frameworks, industry and government can create great innovation business opportunities for industrial sustainability.

Key findings

- ***Almost 30% of direct industrial CO_2 emissions reductions in 2050 in the 2DS hinge on processes that are in development or demonstration today.*** *In the medium term, implementing best available technologies (BATs) and energy efficiency measures, switching to low-carbon fuel mixes and recycling materials are the most effective emission reduction options. Deploying innovative, sustainable processes will be crucial in the long run, with carbon capture and storage (CCS) playing a key role.*
- ***Non-member countries of the Organisation for Economic Co-operation and Development (OECD) are pivotal, accounting for almost 75% of global direct CO_2 emissions reduction from innovative industrial processes in 2050 in the 2DS.*** *As their material demand and share of global markets rise, these countries hold the highest potential for new low-carbon industrial processes. Yet they start from a challenging resources and capacity position, implying greater need for international co-operation and technology transfer.*
- ***Integrating carbon capture, improving resource efficiency, reusing waste process streams and identifying alternative applications for diversified products should be cross-sectoral goals.*** *By sharing their experiences, different industrial sectors and value-chain stakeholders can accelerate learning and cost reduction in these areas, all along production chains.*
- ***Existing measurement methods are inadequate to assess whether sustainability-oriented industrial innovation achieves the intended goals.*** *Traditional input-based innovation statistics relate only to research and development (R&D) and fail to differentiate low-carbon innovation from broader industrial innovation.*
- ***Experience shows the value of stable, long-term policies to promote low-carbon industrial technologies.*** *Long-term support (such as support for entrepreneurship) for the development and demonstration of these technologies attracts innovation investment more effectively than fiscal instruments (such as tax rebates).*
- ***Economic and policy uncertainty, inadequate risk management, unbalanced collaboration and knowledge protection are preventing progress on industrial innovation.*** *Lack of clarity on when climate policies might make low-carbon production globally competitive, coupled with volatile energy prices, makes it difficult for industry to justify investments in sustainable technologies and products.*

Opportunities for policy action

- *By designing stable, long-term, low-carbon strategies – that are aligned internationally – governments can reduce risks and make it worthwhile for industry to reduce its environmental impact. These strategies should be supported by measures such as long-term, legally binding greenhouse gas (GHG) reduction targets, and stable, continuous carbon pricing mechanisms.*
- *In parallel, governments should implement transparent and results-oriented mechanisms for reducing risks for investors in innovative low-carbon industrial technologies. These mechanisms should target progress across a balanced portfolio of technologies and products, chosen to maximise CO_2 emissions reduction. The mechanisms should be linked to long-term, low-carbon strategies, and should include specific market creation measures to promote uptake of low-carbon technologies shortly after their demonstration.*
- *Prioritising focus areas for innovative, sustainable industrial technologies and alternative applications for diversified products should be done through collaboration between government and industry. Insights from both perspectives will better serve the aim of identifying which technologies and products can best contribute to reaching national and regional CO_2 emissions reduction targets.*
- *Creating co-operative innovation frameworks that adequately balance cross-sectoral and international collaboration along product value chains also requires close collaboration. These frameworks should include robust intellectual property (IP) protection mechanisms, and should optimise the potential of public-private partnerships (PPPs).*
- *Collecting output-based statistics with wide sectoral and regional coverage will enable a robust evaluation of the impact of low-carbon industrial innovation. Improving technology richness and robustness of industrial energy use statistics could also contribute to developing performance indicators. Governments and industry should jointly create reporting mechanisms that provide a more accurate picture while adequately protecting commercially valuable data and information.*

Why industrial innovation?

Industrial innovation has played a key role in the development of modern society through continuous improvement of production technologies, and the design of new processes and materials to meet ever-changing societal needs (Box 6.1). In some cases, however, new technology developments have also influenced societal preferences. Historically, investing in innovation has been a successful strategic decision with medium- and long-term economic rewards for companies.

It is remarkable, though, that most of the dramatic industrial process improvements in the energy-intensive manufacturing sectors happened before the 1970s (Freeman and Soete, 1997). These were mainly driven by historical events, such as the reconstruction of Europe and Japan after the Second World War, that raised the need for mass production in manufacturing, higher productivity and new products. As new process technologies are deployed, increasing experience leads to significant performance improvements. As technologies mature, however, this improvement potential falls and innovations are required to boost technology performance.

Industry can innovate by improving manufacturing processes, products or business models. Process innovation involves researching, developing, demonstrating and deploying (RDD&D) process technologies and business models that improve the performance of an industrial activity. Product innovation focuses on developing and commercialising products that have greater added value because of improvements such as higher quality, better mechanical properties and enhanced recyclability.

Box 6.1 Industrial ammonia synthesis transformed food production

The over-fourfold population growth experienced from 1900 to today would probably not have been possible without the development of ammonia synthesis (Smil, 2001).

Nitrogen is a fundamental element for crop production and human growth and survival. Ammonia is one of the most important synthetic chemicals (current global production reaches 165 million tonnes [Mt]), and it is widely used as a precursor of nitrogen-based fertiliser compounds that support about 60% of the world's food production (IFA, 2014).

In the early 1900s, only two methods were available for the production of ammonia, both requiring large amounts of energy: the electric arc method (400 gigajoules per tonne [GJ/t] of ammonia) and the cyanamide method (250 GJ/t of ammonia). The introduction of the Haber-Bosch process for ammonia synthesis drastically reduced the process energy requirements to 100 GJ/t of ammonia (Erismann et al., 2008; IEA, ICCA and Dechema, 2013). The new industrial process was deployed in the rest of the world during the 1920s and 1930s and enabled mass production of fertilisers. Current state-of-the-art ammonia synthesis process based on natural gas-based steam reforming has an energy intensity of 28 GJ/t of ammonia (LBL, 2008).

Process and product innovations are interdependent (Reichstein and Salter, 2006): product innovation often spurs process modifications, while innovative processes may require the development of new materials or may generate useful by-products or upstream industry developments. Businesses tend to perceive product innovation as more important for competitiveness than process innovation (EC, 2014d).

Within the broader concept of industrial innovation, innovation for sustainable industry refers to new processes that directly reduce the environmental impact of manufacturing activities, new products that indirectly enable a reduction of energy consumption or CO_2 emissions, or new business models that favour energy saving and lower CO_2 emissions. Industry was the greatest contributor to global CO_2 emissions in 2012 (40%), including indirect emissions for the production of electricity and oil products consumed. Within the sector, energy-intensive sectors[1] make up 67% of total industrial energy use. Innovation can be determining to support the sector's efforts to realise significant emission reductions.

Enabling growth in production of industrial materials while reducing CO_2 emissions also involves adapting production processes to changing local contexts and societal needs, and taking advantage of cross-sector synergies and interactions along the product value chain.

In some cases, industrial innovation aimed at reducing emissions can also improve productivity, reliability and competitiveness by developing more selective processes with reduced energy costs. For instance, emerging naphtha catalytic cracking processes for olefin production not only enable 10% to 20% energy savings compared with steam cracking[2] (Ren, Patel and Blok, 2006) but also provide a greater overall light olefins conversion yield. Such overlaps make it difficult, and in some cases impossible, to analyse the drivers and challenges in each area separately.

This chapter explores opportunities and barriers influencing industrial innovation progress with an emphasis on specific mechanisms and policy strategies that can contribute to driving industrial innovation towards sustainability.

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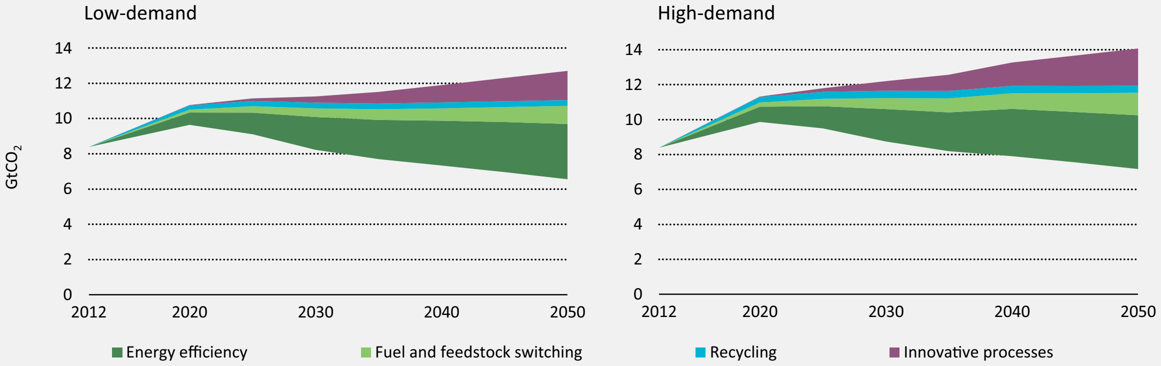
[1] Chemicals and petrochemicals, iron and steel, cement, pulp and paper, and aluminium.

[2] Steam catalytic cracking is the process technology most widely used for light olefin production. Light olefins refer to ethylene and propylene, which are major feedstocks for a variety of chemical products.

Industrial innovation is vital to meet climate targets

Progress over the next decade on sustainability-oriented industrial innovation is crucial to achieve longer-term climate targets in the industrial sector, as well as to reduce CO_2 emissions in other sectors. Of the direct annual CO_2 emissions reductions needed in the sector in 2050 to achieve the 2DS, almost 30% (1.7 gigatonnes of CO_2 [$GtCO_2$]) will have to come from innovative process technologies. Energy efficiency measures, deployment of today's BATs, switching to low-carbon fuel mixes and enhanced material recycling will together lead to 4.5 gigatonnes of direct CO_2 emissions savings (54% of current industrial direct emissions) in 2050, but this will not be enough to achieve the 2DS (Figure 6.1).

Figure 6.1 Direct industrial CO_2 emissions reductions between 6DS and 2DS by technology



Notes: 6DS = *Energy Technology Perspectives* 6°C Scenario. Innovative processes include CCS. Given the uncertainties about projecting long-term materials demand, two variants have been developed for each industrial sector and scenario: a low-demand case and a high-demand case. Globally, the low- and high-demand variants differ by 10% to 35% in terms of projection production levels in 2050. Unless otherwise indicated, numbers refer to the low-demand variant. Figures and data that appear in this report can be downloaded from www.iea.org/etp2015.

Key point *While industrial direct CO_2 emissions peak in 2020 in the 2DS, innovative low-carbon processes become critical to achieve the 2DS in the long term.*

Innovative low-carbon process technologies help to solve specific challenges faced by different industrial sectors while reducing their direct CO_2 emissions. CCS is one of the main contributors to this effort. The identification of synergies among CO_2 capture applications in different industrial sectors through cross-sector collaboration and experience sharing can accelerate learning and cost reduction of these technologies. The deployment of industrial CCS will depend not only on demonstrating its integration in industrial processes but also on developing CO_2 transport infrastructure and storage technologies, and identifying suitable storage locations. Other cross-sector innovation possibilities include making use of waste materials and industrial process streams through enhanced process integration or by finding new applications for these substances that improve resource efficiency and minimise the demand for primary materials. Research is also being carried out on innovative processes that enable the use of non-fossil-based and alternative feedstocks and energy sources, such as biomass, CO_2 and solar thermal.

Industrial researchers are designing and demonstrating **flexible business models that favour energy and CO_2 emissions savings**. Excess industrial heat, for example, can be recovered and used on-site, or sold to industrial neighbours or thermal distribution networks, or used to generate electricity. Such business models can bridge the gap between potential heat sources and sinks when local conditions are favourable, thus contributing to wider CO_2 savings in the overall energy system.

Product innovation also offers promising avenues for sustainable industry. A mapping exercise of scientific patents concluded that materials science and chemistry were more important for low-carbon technology developments than energy and environmental science (OECD and World Bank, 2014). Systemic approaches such as life-cycle assessments (LCAs) explore the overall CO_2 mitigation impact of a specific product, among other environmental impacts, by considering not only emissions savings at the manufacturing stage but also the effect on energy consumption at the use phase, and in some cases, possible recycling routes. By considering these aspects at an early stage, products can be designed to maximise sustainability benefits right along the value chain. Developing policies that foster these systemic approaches can be difficult, however, as it requires a deep understanding of cross-sectoral synergies.

Box 6.2

LCAs can reveal opportunities for innovative sustainable products

Environmental and energy-cost awareness among consumers can create opportunities for product innovation. LCAs are one way of determining where energy is being used and can be saved. Specifying comprehensive system boundaries for LCAs is critical to ensure meaningful analysis and avoid missing important factors.

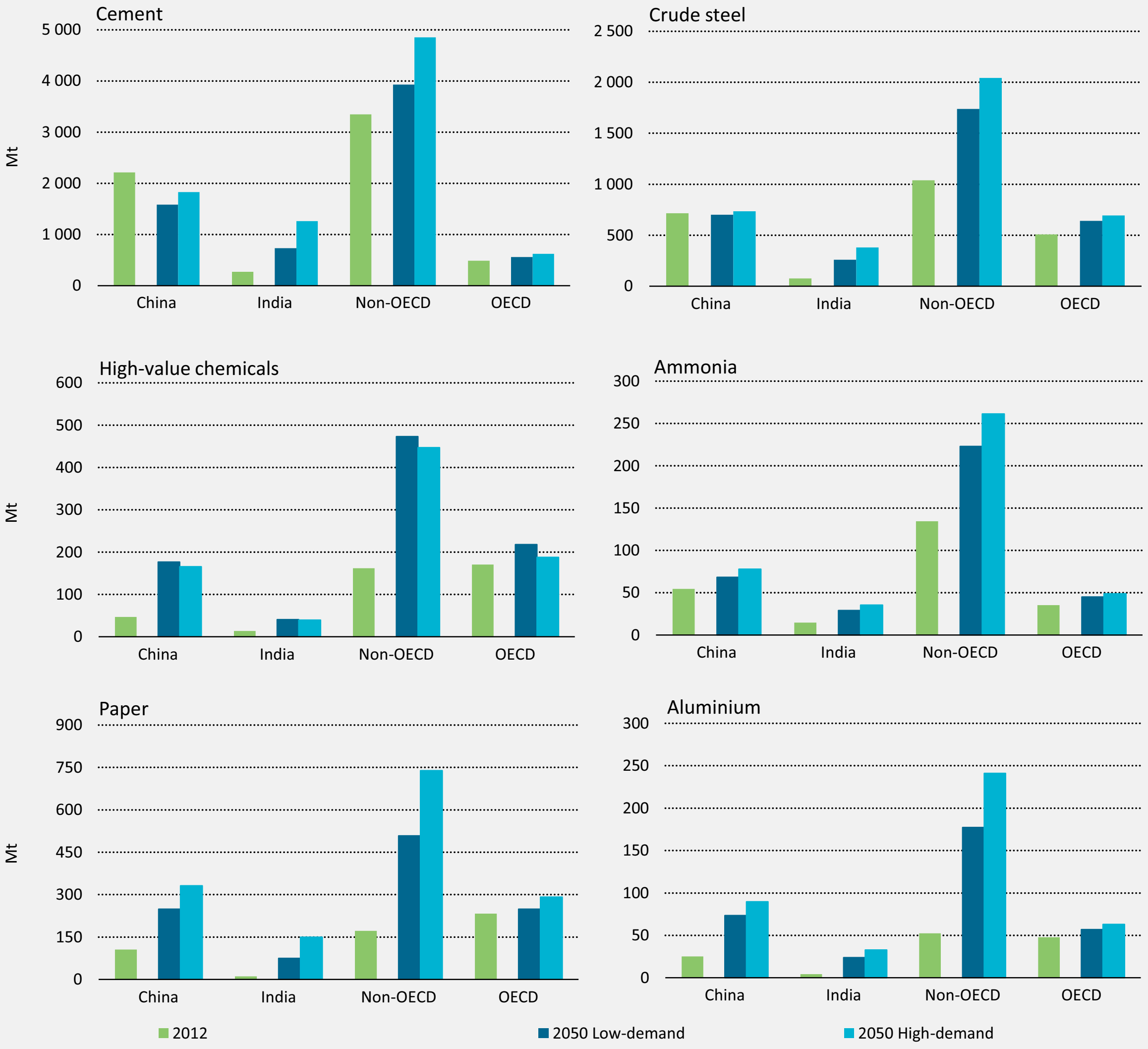
Procter & Gamble, a multinational company providing a wide range of consumer goods for household care, beauty and grooming, performed an energy profile in 2002 of its major product categories during their life cycles. Energy used in homes to heat water and wash clothes was found to be the major contributor to energy consumption, and thus GHG emissions, followed by materials and products manufacturing (White, 2009). In response, researchers developed detergents that could clean clothes better at temperatures below 30°C. The use of these can reduce energy use per wash by 40% (estimate for Western Europe). More recently, Procter & Gamble and DuPont jointly developed a product that provides better cleaning performance below 15°C, based on a new enzyme called protease, for which the companies received the 2014 Sustainable Bio Award for Bio-Based Product Innovation of the Year. In the United States, consumers could save 32.3 million tonnes of CO_2 ($MtCO_2$) emissions annually by washing clothes at low temperatures (White, 2009; DuPont, 2014).

The critical need for a global sustainable push to industrial innovation

To realise the direct CO_2 emission cuts in the 2DS, the industrial sector needs to make a global effort. As regions face different demand for industrial materials, energy price prospects, and policy and regulatory outlooks, international co-ordination becomes more relevant to overcoming diverse regional challenges to the deployment of innovative sustainable industrial processes.

Based on historical trends of industrial production and projected growth in population and gross domestic product (GDP), global demand for most industrial materials is expected to continue to increase over the next 40 years. While long-term growth in demand for some materials is expected to slow down in China (and even decline, after peaking around 2020, as in the case of cement and crude steel), industrial materials production is anticipated to accelerate in most OECD non-member economies. In the Middle East and Africa combined, and in Other Asia (excluding China and India) cement production is likely to double and crude steel production rise over sixfold by 2050. Cement and crude steel production is expected to triple in India by 2050, as does production of paper and high-value chemicals[3] (HVC) in OECD non-member economies. Industrial production growth shows a more modest increase in OECD countries, where consumption levels are already considered mature and the population is projected to grow at a lower rate (Figure 6.2).

Figure 6.2 **Materials production by region, 2DS**



Notes: materials production values for 2050 refer to the 2DS. In 2050, high-value chemical production is lower in the high-demand variant than in the low-demand variant because of the greater effect of increased plastic recycling rates in the 2DS.

Key point *The greatest growth in materials production is expected to occur in OECD non-member economies in the period 2012 to 2050.*

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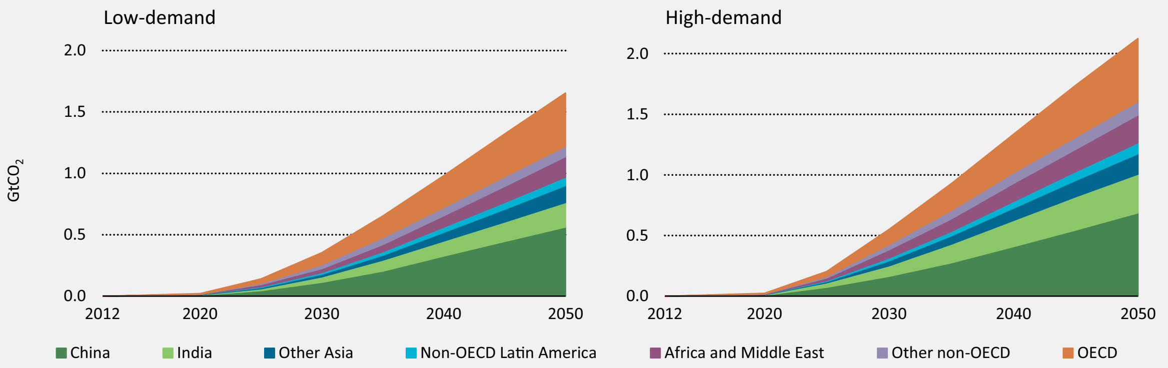
[3] High-value chemicals refer to ethylene, propylene and BTX (benzene, toluene and xylene).

Implementing low-carbon process technologies can be more difficult technically and operationally in regions that expect stable or moderate materials production growth than in regions that expect to add greater levels of industrial production capacity in the near future. Equipment retrofits or replacements can create bottlenecks as upstream or downstream equipment reaches technical capacity limits. Together with the impact of local factors such as space constraints, material compatibilities and process units' connections with other units, this may prevent new processes from achieving optimum performance. By the same token, deploying an innovative industrial process in a new site can enable the plant design to be technically and economically optimised by taking local factors into consideration beforehand.

Growing material demand in OECD non-member economies and the increasing importance of these countries in global markets increase their potential to deploy innovative industrial process technologies more widely as they add new capacity. This is reflected in the 2DS, in which OECD non-members contribute 74% of global direct CO_2 emissions reductions resulting from innovative low-carbon industrial processes by 2050 (Figure 6.3).

To enable the global spread of innovative processes, products and business models, co-operative research and technology transfer are essential, especially between countries whose strength lies in R&D and countries that may have more attractive conditions for demonstration and deployment.

Figure 6.3 Direct CO_2 emissions reductions between 6DS and 2DS from innovative processes by region



Key point *OECD non-member economies contribute almost three-quarters of the global industrial CO_2 emissions reductions resulting from innovative processes by 2050 in the 2DS.*

Innovation opportunities for sustainable industry, sector by sector

To develop and implement innovative low-carbon technologies, each industrial sector needs to understand and deal with its own specific challenges.[4] Availability and quality of raw materials and feedstocks may be limited. Products may vary widely in how easily they can be traded or recycled. Along each product's value chain, the proportion of CO_2 emissions that

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[4] This section presents some of the main innovation avenues that are currently being explored, and it is not intended to provide an exhaustive list.

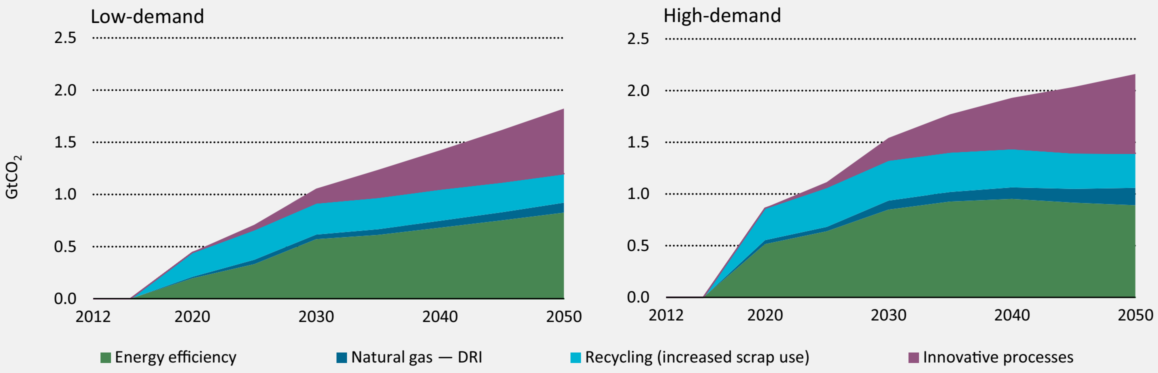
arise from the manufacturing phase may differ. All these aspects need to be well understood and addressed to achieve this global sustainability endeavour.

Iron and steel sector

In the 2DS, direct CO_2 emissions in the iron and steel sector are 55% lower in 2050 than in the 6DS (a reduction of 1.8 $GtCO_2$), even though global crude steel production is likely to grow by almost 50%. Emissions can be significantly reduced globally by improving energy efficiency, phasing out outdated technologies, switching existing processes to a lower-carbon fuel (e.g. shifting from coal to gas-based direct reduced iron [DRI]) and recycling more steel to increase the availability of scrap. Even so, about 35% of the emissions reductions required in 2050 hinge on the development, demonstration and deployment of innovative low-carbon processes and products (Figure 6.4). Such innovative low-carbon processes are expected to become even more important after 2030, when the contribution of energy efficiency measures to the sector's direct emissions reductions will slow down as BATs become widespread.

OECD countries have a role in deploying and transferring innovative iron and steel technologies, but OECD non-members have greater potential to deploy innovative low-carbon processes because their demand for materials is expected to grow faster. In the 2DS, 64% of global direct CO_2 emissions reductions from new iron- and steel-making processes in 2050 occur in OECD non-member economies with China accounting for 35% and India 13%.

Figure 6.4 Global iron and steel direct CO_2 emissions reduction between 6DS and 2DS by technology



Note: Innovative processes include CCS.

Key point *Around 35% of required CO_2 emissions reductions in the iron and steel sector in 2DS in 2050 hinges on deployment of innovative processes.*

To develop low-carbon processes, the iron and steel sector will have to surmount obstacles such as limited availability of scrap and decreasing quality of coal and iron ore, which raises energy use.

Among available process routes for making iron and primary steel, the blast furnace (BF) and basic oxygen furnace (BOF) route is the least energy-intensive in global average performance standards, at 18.7 GJ/t of crude steel, followed by the smelt reduction (SR) iron making with BOF (21.4 GJ/t of crude steel), and DRI and electric arc furnace (EAF)

(22.4 GJ/t of crude steel). The production of steel from 100% scrap-based EAF has significantly lower energy requirements: 6.7 GJ/t of crude steel (Worldsteel, 2014).[5] The gas-based DRI process route leads to direct CO_2 emissions savings but can be limited by economic availability of scrap: best practice DRI-fed EAFs consume 40% scrap and 60% DRI (LBL, 2008).

Low-carbon innovation efforts in the iron and steel sector focus on increasing the energy efficiency of existing processes and integrating carbon capture. Technical avenues include improving process integration, optimising the use of process gas streams as iron ore reducing agents and exploring the possibilities of oxygen-rich conditions.

- **CCS is being applied to existing iron-making technologies,** such as gas-based DRI. A facility capturing 800 kilotonnes of CO_2 per year (ktCO_2/yr) from a DRI-based site is under construction in the United Arab Emirates and is scheduled to begin operation in 2016. The captured CO_2 will be used for enhanced oil recovery (Global CCS Institute, 2014).
- **BF top gas recovery with carbon capture** is a process technology developed by the Ultra-Low Carbon Dioxide Steelmaking (ULCOS) European research programme. Top gas, a by-product of BFs, is collected, treated and reused as a reducing agent, displacing coke use. The BF top gas recovery system (BF-TGR) also operates with pure oxygen, enabling a higher concentration of CO_2 in the top gas and thus easier carbon capture (Birat, 2010). A commercial-scale plant planned for the ArcelorMittal site in Florange, France, in 2013 was stopped for financial reasons.
- **Ulcored,** a DRI-based process, was also developed by ULCOS. DRI is produced by reducing iron ore in a shaft furnace with reducing gas from coal gasification or gas reforming. Off-gases from the shaft are reused in the process after CO_2 capture (Birat, 2010). In 2013, there were plans to build a pilot plant that produces 1 tonne of DRI per hour to demonstrate this process. However, these plans have not materialised at the time of writing this report (LKAB and ULCOS, 2013).
- **HIsarna,** an SR process developed by ULCOS, combines a hot cyclone and a bath smelter, and does not require the use of coke or sinter. As the process operates with pure oxygen, off-gases have a CO_2 concentration almost high enough to be directly stored (Birat, 2010). Commercial-grade steel was first produced through the HIsarna process in 2013 and continued in June 2014 supported only with private funding. A longer trial of about 90 days to test process stability and continuous operation is planned for 2016. The outcome of this trial will determine design parameters for a commercial-scale plant (ESEC, 2014).
- **Coke oven gas (COG) reforming** is a process that partially converts carbon compounds of COG into hydrogen and carbon monoxide. The COURSE 50 programme in Japan (CO_2 Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 50) is developing a process that uses this technique to produce enhanced reducing gas for BF, coupled with CO_2 capture. The principle is to increase the hydrogen content of COG from an average of 55% to between 63% and 67% by reforming tar contained in the gas mixture, to reduce coke needs for iron ore reduction and to reduce CO_2 emissions from BFs by 30% (Tonomura, 2013). An experimental BF for testing a hydrogen-enriched reducing agent is planned to be built by 2017 (ESEC, 2014). The Korean steel maker POSCO and its Research Institute of Industrial Science (RIST) are also developing a conversion process to produce a hydrogen-rich gas from COG and CO_2 through steam reforming, which could be used for iron ore reduction in a BF or SR process. The design of the COG reforming process was completed in 2012 and a pilot plant is currently under construction (RIST, 2013).

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[5] Energy intensity values are provided as global performance averages in final energy terms including electricity and covering from material input preparation to hot rolling.

- **Ulcowin and Ulcolysis, developed by ULCOS, are electricity-based process concepts that produce iron using electrolysis reduction systems**. Ulcowin consists of an aqueous electrolysis of iron oxide at 110°C. The principle of Ulcolysis is the decomposition of iron ore into oxygen and liquid metal at 1 550°C in a similar manner to the Hall-Heroult aluminium production process. Both concepts have been proven at experimental scale. Wider sustainability benefits of these processes rely on the use of renewable-based or carbon-free electricity.

Researchers are also exploring ways of reusing waste gases produced in the BF and BOF processes. Commercial processes already exist to use COG for methanol production; in 2009, China's methanol production capacity from COG was 4 Mt (R&M, 2010). The first pilot plant to produce ethanol from unused BF gas was built and operated in Shanghai, China, in 2012, and a commercial-scale plant is expected to start up at the end of 2015. Funding is being sought to continue research on producing more complex petrochemical products and fuel-grade ethanol (ESEC, 2014; Platts, 2013).

The role of innovative iron and steel processes in the 2DS strongly depends on technology characterisation parameters such as expected commercial availability, CO_2 process footprint, related investment costs and local conditions. Thus the 2DS least-cost technology pathway is significantly sensitive to how innovation progresses in the sector in the medium term. If the innovative iron and steel processes discussed here (Table 6.1) reach successful commercial-scale demonstration, the most cost-competitive option in the 2DS appears to be SR coupled with carbon capture, considering limitations of economic availability of scrap in the 2DS.

Table 6.1 Main innovative low-carbon technology options in the iron and steel sector

Process	Type	Research programme	Current status	Considered availability date	Energy intensity (GJ/t material)	Reference capital expenditure (USD/t material)
CO_2 capture	BF/DRI/SR	Several	Pilot phase	2016 *	95-170 kWh/tCO_2 2 GJ/tCO_2 ***	80-143 USD/tCO_2
BF-TGR	BF	ULCOS	Pilot phase	2025	12.2	337-240
Ulcored	DRI	ULCOS	Pilot phase	2030	8.7	350
HIsarna	SR	ULCOS	Pilot phase	2030	12.2	140
COG reforming – hydrogen amplification integration	BF/SR	COURSE 50/ POSCO-RIST	Pilot phase	2030 **	..	..
Ulcolysis/Ulcowin	Electricity reduction	ULCOS	Laboratory	..	..	..

Notes: ".." indicates data is not available; kWh = kilowatt hour; GJ = gigajoule; tCO_2 = tonnes of CO_2; t = tonne. This list is not exhaustive and should be considered with caution as these technologies are at demonstration phase. Energy intensity and investment values for technologies under development or demonstration are uncertain due to a lack of technology performance data at commercial scale. Energy intensity values include electricity and are comparable only for processes of the same type. Capital expenditure values refer to the base year and new-built capacity. Plant cost excludes costs for contingency, fees and owner costs, as well as CO_2 transport and storage costs. Plant cost for technologies operating with oxygen-rich conditions excludes air separation unit (ASU) cost. Oxygen and amine solvents are considered exogenous commodities purchased at a base price of USD 128 per normal cubic kilometre (kNm^3) and USD 1.52 per kilogramme (kg) respectively.

* CCS applications related to innovative processes are considered to be available after 2016 as per the respective core process.

** COURSE 50 project's milestones aim at having the first production unit in operation by 2030, assuming CO_2 transport and storage is economically viable by then.

*** Thermal energy demand is considered only for CO_2 capture techniques based on amine scrubbing. Electricity consumption varies depending on the specific capture technique considered.

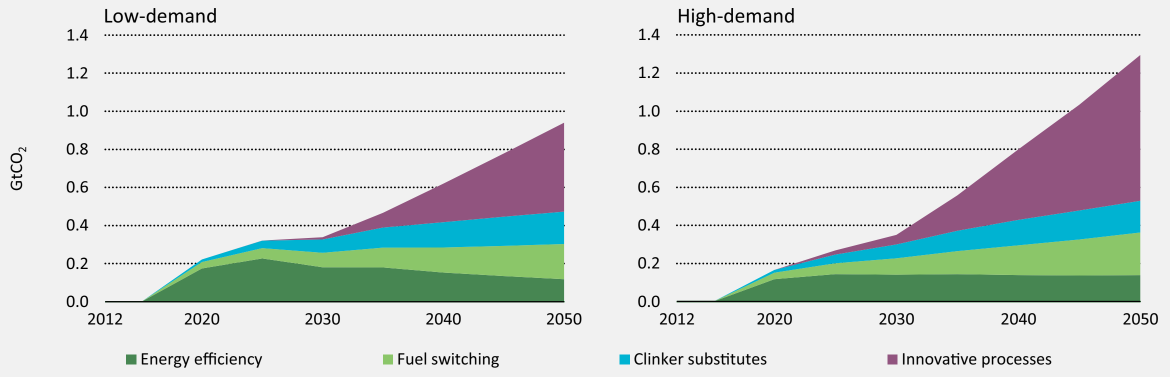
Sources: GHG IA (2013), *Iron and Steel CCS Study (Techno-Economics Integrated Steel Mill)*, GHG IA, Cheltenham; BCG (Boston Consulting Group) and VDEh (Steel Institute and Association of German Steel Manufacturers) (2013), *Steel's Contribution to a Low-Carbon Europe 2050*, BCG, Boston; EC (2012), *Prospective Scenarios on Energy Efficiency and CO_2 Emissions in the EU Iron and Steel Industry*, Joint Research Centre, Brussels; ETSAP IA (2010), "Iron and steel", *Technology Brief I02*, May; LBL (Lawrence Berkeley National Laboratory) (2008), *World Best Practice Energy Intensity Values for Selected Industrial Sectors*, LBL, Berkeley, California; Birat, J.P. (2010), *Steel Sectoral Report: Contribution to the UNIDO Roadmap on CCS*; Knop, K., M. Hallin and E. Burstorm (2008), "ULCORED SP 12 Concept for minimized CO_2 emission", Vol. 106/10, *La Revue de Métallurgie*, pp.419-421; IEA (2007), *Tracking Industrial Energy Efficiency and CO_2 Emissions*, OECD/IEA, Paris; IEA estimates.

Innovative and high value-added products, which are gaining relevance as a strategic choice for companies, offer further opportunities to reduce CO_2 emissions in the iron and steel sector. They can also improve sustainability in other sectors, such as transport, buildings and energy supply. For instance, the Institute of Energy Economics in Japan estimated that 23 $MtCO_2$ were saved in 2011 (9 $MtCO_2$ from domestic use and 14 $MtCO_2$ from exports) through the use of high-performance steel products in equipment such as industrial motors, high-efficiency boilers, energy efficient transformers, innovative or "next-generation" automobiles, and renewable power generation equipment. These value-added steel products have enhanced characteristics such as better resistance to corrosion and high temperatures, and improved electromagnetic properties that increase final equipment performance (JISF, 2012).

Cement sector

With global cement production expected to increase 17% by 2050, the sector will need to implement a range of measures to achieve the CO_2 emissions reductions in the 2DS (Figure 6.5). Cement producers can increase energy efficiency by reducing thermal and electricity intensities to approach dry-process[6] BAT performance levels. They can maximise the substitution of clinker, an intermediate product in cement production.[7] And they can replace current fuels with low-carbon fuel mixes. These measures, along with plant heat integration, can save 473 Mt of direct CO_2 emissions in 2050 (21% of current direct CO_2 emissions in the sector).

Figure 6.5 Global cement CO_2 emissions reduction between 6DS and 2DS by technology



Note: Innovative processes include CCS.

Key point *Between 50% and 60% of required CO_2 emissions reduction in the cement sector in 2DS in 2050 relies on deployment of innovative processes.*

The 2DS requires further emissions reductions, however, so it will be crucial to demonstrate and implement low-carbon technologies, especially CCS; such technologies allow 467 $MtCO_2$ to be captured globally in 2050 in the 2DS (20% of current direct CO_2 emissions). OECD non-member economies will account for 84% of this amount, and OECD non-member Asian countries 61%.

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[6] BAT for the cement sector is considered the dry-process kiln with a six-stage pre-heater and pre-calciner (2.9 GJ/t clinker) (IEA, 2007).

[7] Clinker is the result of calcination of limestone in the kiln and subsequent reactions caused through burning.

To achieve this goal while maintaining cement standards, the sector will have to overcome obstacles that could hinder the spread of innovative technologies, such as limited availability and quality of alternative fuels, and clinker substitutes that are, in some cases, influenced by the activity of other industrial sectors (e.g. BF slag is a waste stream produced in the iron and steel sector that can be used for clinker substitution).

Research on the use of alternative fuels and raw materials (AFRs)[8] aims to identify and simulate the right combustion conditions and to assess operational health and safety risks for each alternative fuel or raw material (IEA and WBCSD, 2013). A 5 kilotonne (kt) per day clinker facility was commissioned in 2013 in Liyang (China) to demonstrate co-processing of municipal solid wastes for clinker-making (Sinoma Research Institute, 2014).

New technologies that could improve the sustainability of the cement sector focus on direct capture of CO_2 emissions and reducing the thermal intensity of cement production (Table 6.2).

- **Post-combustion carbon capture in cement kilns** does not require fundamental changes in the clinker-making process and can be implemented in existing facilities where there is enough space for the additional equipment (IEA and WBCSD, 2013). Chemical absorption, the most investigated separation technique, increases the thermal energy requirements of the cement plant to support solvent regeneration. Other separation techniques are also being studied, including adsorption, membrane, calcium looping and mineralisation. In the period 2013-17 several separation technologies (amine scrubbing, dry adsorption, membranes and carbon looping) are expected to be studied at the test facility in Brevik, Norway, through small-scale or pilot trials of post-combustion carbon capture from the cement plant flue gas. A pilot plant using calcium looping to capture 1 tCO_2 per hour was commissioned in 2013 in Chinese Taipei. Processes are also being developed to capture and transform CO_2 into sellable products such as calcium or sodium carbonate. A plant has been constructed in Texas to capture and transform 75 $ktCO_2$/yr from a cement plant into sodium bicarbonate, bleach and hydrochloric acid, which can be sold in the market (GHG IA, Global CCS Institute and ECRA, 2013; Skyonic, 2014).

- **Oxy-fuel combustion for carbon capture in cement kilns** uses oxygen-enriched gas to support the combustion process, which increases the concentration of CO_2 in the flue gases. Even if it does not increase the site's fuel consumption, its implementation requires re-engineering the plant to accommodate the equipment to the oxygen-rich combustion, as well as a good understanding of the impacts of these operating conditions. It also incurs additional operating costs for the provision of oxygen (IEA and WBCSD, 2013). The implementation of oxy-fuelling in the kiln pre-calciner was tested in a pilot plant capturing 1 tCO_2 per hour in Dania, Denmark, with positive results that lead to a feasibility and costs study of retrofitting this technology to an existing commercial-scale facility in Le Havre, France (GHG IA, 2014).

  Applying oxy-combustion only at the pre-calciner stage (partial oxy-fuelling) has some advantages over full oxy-fuelling, such as minimising the impact of high-CO_2 conditions in the kiln and the air leakage that dilutes the CO_2 in the flue gases. The CO_2 capture rate with partial oxy-fuelling is 60%, whereas with full oxy-combustion it is 90% of the direct cement plant emissions (GHG IA, 2008).

  Even if partial oxy-fuelling has a lower capture rate than post-combustion, this capture option is found more cost-competitive in the 2DS. There are other considerations that may limit the real uptake of partial oxy-fuelling carbon capture, such as the need for equipment re-engineering compared with a less disruptive end-of-pipe installation required by

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[8] AFRs include wastes that would otherwise be burned in incinerators, dumped in landfills or improperly destroyed.

post-combustion capture. Both innovative capture options require additional utility facilities: a generation unit to provide additional thermal energy for the regeneration of used amine solvents in post-combustion capture, and the provision of an ASU to supply oxygen for oxy-fuelling.

The contribution of carbon capture processes in the 2DS hinges on factors such as technology readiness, related investment costs, ease of implementation in existing plants, emissions reduction potential, and local conditions such as energy prices and the availability of clinker substitutes. The 2DS least-cost trajectory will be influenced by the evolution of these innovative applications in the medium term.

Table 6.2 Main innovative low-carbon technology options in the cement sector

Process	Current status	Considered availability date	Energy intensity	Capture rate (%)	Capital expenditure (USD/tCO_2 captured)
Post-combustion CO_2 capture	Pilot phase	2020	237 kWh/tCO_2 2 GJ/tCO_2	90	263
Partial oxy-fuelling CO_2 capture	Pilot phase	2025	138 kWh/tCO_2	60	101

Notes: Capital expenditure values refer to the base year. Plant cost excludes costs for contingency, fees, and owner costs, as well as CO_2 transport and storage costs. Oxy-fuelling plant cost also excludes Organic Rankine Cycle heat recovery unit and ASU. Oxygen and amine solvents are considered exogenous commodities purchased at a base price of USD 128/kNm^3 and USD 1.52/kg respectively.
Sources: GHG IA (2008), "CO_2 capture in the cement industry", *Technology Study*, Report No. 2008/3, GHG IA, Cheltenham, www.globalccsinstitute.com/sites/www.globalccsinstitute.com/files/publications/95751/co2-capture-cement-industrypdf.pdf; GHG IA, Global CCS Institute and ECRA (European Cement Research Academy) (2013), *Deployment of CCS in the Cement Industry*, http://ieaghg.org/docs/General_Docs/Reports/2013-19.pdf.

In the cement sector, as in other sectors, low-carbon products may offer opportunities to reduce CO_2 emissions. Some cement companies are developing low-carbon cements with properties similar to those of ordinary Portland cement. Combining non-carbonate raw material with CO_2 absorption and the use of low-carbon fuels could even lead to the production of carbon-negative cements (IEA and WBCSD, 2013).[9]

- In 2011, the **Aether** clinker project proved the feasibility of industrial-scale production of low-carbon clinker with 25% to 30% less CO_2 emissions per tonne of cement than a standard process. Further trials are under way (IEA and WBCSD, 2013).
- **Calix** cement is produced by rapid calcination of dolomitic rock in superheated steam. This process can also enable carbon capture through CO_2 scrubbing (IEA and WBCSD, 2013).
- According to its developers, **Celitement** is a novel cement produced through a process emitting 50% less CO_2 than standard processes, with low consumption of limestone and gypsum additive. As of 2013, a pilot plant was in operation to demonstrate the principles of the process (IEA and WBCSD, 2013).

Chemicals and petrochemicals sector

There is significant potential to reduce CO_2 emissions in the chemicals and petrochemicals sector through efficiency advances and innovative catalytic processes, as outlined in a technology roadmap developed jointly in 2013 by the International Council of Chemical Associations (ICCA), Dechema (Society for Chemical Engineering and Biotechnology) and the International Energy Agency (IEA). While incremental improvements and best practice

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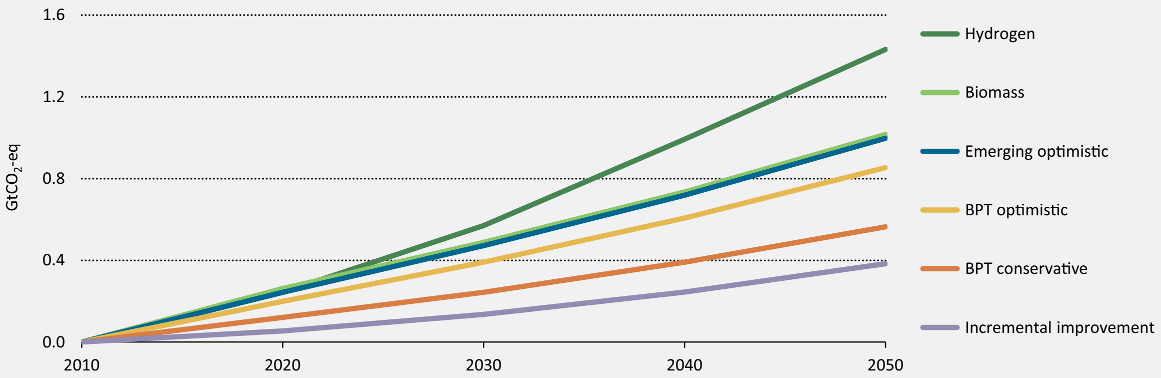
[9] Some low-carbon cements are presented in this section. This is not intended to be an exhaustive list.

technologies (BPTs) that reduce the energy intensity of catalytic processes could save the equivalent of about 0.9 $GtCO_2$ by 2050, deploying emerging technologies and some selected game-changer options could provide additional savings equivalent to 0.6 $GtCO_2$ (Figure 6.6).

Figure 6.6 Global GHG emissions reduction from catalytic processes in the chemicals industry



Notes: $GtCO_2$-eq = gigatonnes of CO_2-equivalent. Incremental improvement describes all improvements carried out on a chemical or petrochemical plant during its operational lifetime without major retrofits. BPT describes the most energy efficient process technologies available at a given moment in time. Within the projection, a conservative BPT option and an optimistic BPT option describe different rates of implementation of BPT compared with the average technology in newly built and retrofitted plants. Emerging technologies have demonstrated technical viability and have a high potential of being economically competitive on an industrial scale. Two potential game changers are considered: the use of hydrogen from renewable sources to produce ammonia and methanol, and the use of biomass as feedstock via fermentation of sugar-/starch-rich biomass to ethanol and then to ethylene by dehydration, or via biomass gasification to synthetic gas, which is then used for methanol production, and later olefin production via the methanol-to-olefin route.

Source: IEA, ICCA and Dechema (2013), *Technology Roadmap: Energy and GHG Reductions in the Chemical Industry via Catalytic Processes*, OECD/IEA, Paris.

Key point *Catalyst and related process improvements could save the equivalent of 1 $GtCO_2$ per year by 2050.*

Since the release of the roadmap, industry representatives and the US government have discussed opportunities for pre-commercial R&D, fundamental obstacles that R&D could address, and a path to overcome these in collaboration with academia, research institutions and other interested parties. The American Chemistry Council has established a working group to promote R&D on catalytic processes. R&D is also focusing on other relevant technologies, such as separation processes and carbon capture.

- **Naphtha-based catalytic cracking for production of olefins**[10] shows 10% to 20% energy savings compared with the widely used steam cracking process (Ren, Patel and Blok, 2006). It can also provide greater overall light olefin conversion: the Advanced Catalytic Olefins process has a 10% to 25% greater light olefin conversion than conventional naphtha steam cracking depending on the operating conditions and feed quality (Tallan et al., 2011). Catalytic cracking process technologies have been developed by several organisations, such as the Korean Research Institute of Chemical Technologies (KRICT) and an alliance of Saudi Aramco, JX Nippon Oil & Energy and King Fahd University of Petroleum and Minerals. After successful pilot testing, in 2010 the first commercial catalytic cracking plant was constructed in Korea based on KRICT technology, with a capacity of 40 kilotonnes per year (kt/yr) light olefins (Tallan et al., 2011).

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[10] The most important olefins are ethylene and propylene. These are major feedstocks for a variety of chemical products.

- While the **methanol-to-olefin (MTO)** route is more energy-intensive than steam cracking when including the methanol production stage, it enables the production of light olefins from gas and coal, as well as from biomass in the longer term. MTO technologies licensed by UOP/Norsk Hydro, SYN Energy Technology Co. Ltd./Lummus Technology and others have entered commercialisation (Barger, Vora and UOP, 2003).
- The use of **biomass as feedstock for chemicals production** is being explored by many research projects, pilot plants and semi-commercial plants. Biomass can be used to produce light olefins and subsequent products in several ways, including biomass gasification with subsequent MTO, or biomass fermentation to ethanol followed by dehydration into ethylene. The energy consumption of these biomass-based routes is 3.5 to 5 times greater than fossil fuel-based routes overall, so emissions reduction benefits should be weighed against energy requirements (IEA, ICCA and Dechema, 2013). Reducing energy consumption and costs in current biomass-based chemical production are areas for further research.
- **Low-carbon hydrogen generation could reduce energy requirements for producing ammonia and methanol**, as hydrogen generation is one of the most energy-intensive stages within these processes. Catalysts could enable photocatalysis or photovoltaic-assisted water electrolysis, which are at the fundamental research phase, opening new research avenues for less CO_2-intensive ammonia and methanol production processes.
- **Enhanced membrane separation techniques** involve a wide range of research activities. Innovative nature-inspired mechanisms for membrane synthesis, including nanoscale surface patterning and self-organisation, are aimed at improving the sustainability of separation processes (Jullok, 2014).
- While **carbon capture applications** are mature in ammonia and methanol production processes that generate high-purity CO_2 gas streams, carbon capture techniques in steam cracking, as well as from diluted CO_2 flue gas streams generated in chemical production sites, have yet to be scaled up (IEA, 2011; IEA, 2013a).

Among the emerging technologies analysed, naphtha-based catalytic cracking for olefin production could lead to overall energy savings of 30% to 40%, if this technology replaces some older steam naphtha crackers (IEA, ICCA and Dechema, 2013). Using biomass as a feedstock and renewable-based hydrogen to produce ammonia and methanol could bring about a major change in energy consumption or related emissions in the sector. Replacing 30% of current ammonia and methanol production with direct use of renewable-based hydrogen would be more energy-intensive (2.4 exajoules additional energy use by 2050), but could save the equivalent of 200 $MtCO_2$. Significant technical barriers will need to be overcome to drastically reduce the energy needs of hydrogen generation from renewable sources to allow enough supply through this route for this shift to realistically occur.

Similarly, biomass-based routes for producing olefins are 3.5 to 5 times more energy-intensive than fossil fuel-based standard routes, despite their advantages from an emissions perspective. Producing HVC from sugar cane through the MTO route could save 4.16 tonnes of CO_2-equivalent per tonne (tCO_2-eq/t) of HVC and from lignocelluloses 3.65 tCO_2-eq/t of HVC compared with the widely used fossil fuel-based steam cracking. Again, energy consumption and costs would have to fall for these process routes to be widely deployed (IEA, ICCA and Dechema, 2013).

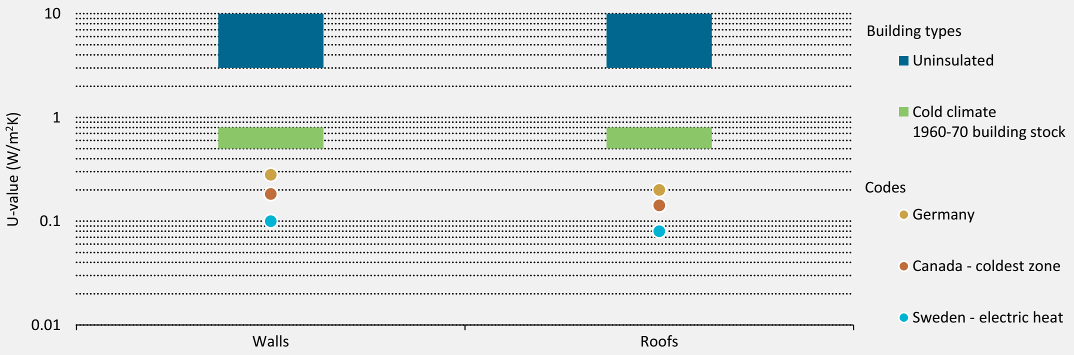
A large number of research activities in the chemicals and petrochemicals sector are pursuing the development of **innovative materials and products** that indirectly improve the sustainability of other sectors. Lighter organic materials for transportation improve vehicles' fuel economy, for example, and resource-efficient building materials have great potential for direct reuse and recycling (Box 6.3).

Box 6.3 Tighter building envelopes driving innovative material developments

The building envelope is the boundary between the conditioned interior of a building and the outdoors. Thus, the energy performance of its components is critical in determining building energy requirements for heating and cooling. Globally, space heating and cooling count for over one-third of buildings' energy use, increasing to 50% in cold climates and over 60% in the residential sub-sector in similar climate conditions.

Higher-performing insulating materials developed by the chemical and petrochemical industries provide energy efficient solutions for buildings. Stringent energy codes for new buildings, based on affordable technological options adapted to local conditions and rated in accordance with harmonised testing and certification standards, can drive the development of sustainable innovative products in the manufacturing industry. New material developments, such as highly insulated windows, high-performance insulation, less labour-intensive air sealing, lower-cost automated dynamic shading and glazing, and more durable and lower-cost reflective roof materials and coatings, could further contribute to improving building envelopes. As greater emphasis is placed on LCAs, including energy and disposal impacts, there may be significant interest in reducing the environmental impact of building material production.

Figure 6.7 Average existing building insulation levels and building code requirements



Notes: W/m^{2}K = watts per square metre and degree Kelvin. U-value refers to the overall heat transfer coefficient that defines the energy performance of a specific element.
Source: IEA (2013c), *Technology Roadmap: Energy Efficient Building Envelopes*, OECD/IEA, Paris.

Key point *Buildings insulation level varies widely depending on climate conditions and on building stock characteristics.*

Pulp and paper sector

Low-carbon innovation efforts in the pulp and paper sector focus on demonstrating biomass conversion processes and CCS.

- Biomass conversion processes such as **black liquor gasification** (BLG) enable generation of electricity, production of bio-chemicals and bio-refinery operations to produce synthetic fuels. Several BLG pilot plants are in operation, ranging from 20 t per day to 300 t per day, in Canada, Sweden and the United States, but no commercial-scale sites. Further research is needed to improve process control and reliability, and synthesis gas clean-up (Naqvi, Yan and Dahlquist, 2010).

- **CCS** applications in pulp and paper-making processes, either from biomass conversion processes or from flue gases generated at process heaters and other captive utilities, are yet to be demonstrated.

Further avenues are being explored to make use of off-gases generated in pulp and paper processes. A new process for extracting and purifying bio-methanol from stripper off-gas, a pulp mill waste stream, has been implemented at a site in Alberta, Canada. The produced bio-methanol is used on-site to support pulp whitening operations and displaces fossil fuel-based methanol imports (NRCAN, 2013).

Other innovation research in the pulp and paper sector focuses on identifying breakthrough technologies that could reduce direct CO_2 emissions. In 2013, for example, laboratory-scale results showed it is possible to produce pulp at low temperature and atmospheric pressure by using deep eutectic solvents with drastically reduced energy requirements (CEPI, 2013).

The pulp and paper sector and the wood and wood products industry are exploring routes for **bio-product diversification**. For instance, lignin extracted from pulping liquor can be used to replace fossil fuels or modified to replace fossil fuel-based materials. A demonstration plant started in 2007 at Bäckhammar, Sweden, as a result of a joint research programme between industry and academia. The first full-scale lignin extraction plant was started in 2013 at Plymouth, North Carolina (Tomani, 2009; Valmet, 2014). Other bio-product diversification routes include the conversion of kraft market pulp mills to produce dissolving pulp for the textile industry in Canada (FPAC, 2012), and a collaboration between the US forest products company Weyerhaeuser and Ford Motor Company to assess the potential to develop car parts reinforced with cellulose fibre (FPAC, 2014).

Aluminium sector

Research on reducing direct CO_2 emissions in the aluminium sector focuses on two alternative technologies to the widely used Hall-Heroult electrolysis process, but neither has reached the commercial stage yet.

- **Direct carbothermic reduction of alumina** could reduce energy consumption by 21% but has substantially lower aluminium conversion yields than standard processes. Researchers are looking at ways of resolving this issue, such as vacuum carbothermic reduction (Balomenos et al., 2011).
- **Kaolinite reduction** could reduce on-site energy requirements by 15% and use domestically available ore but would increase the amount of materials required by the process (Green, 2007).

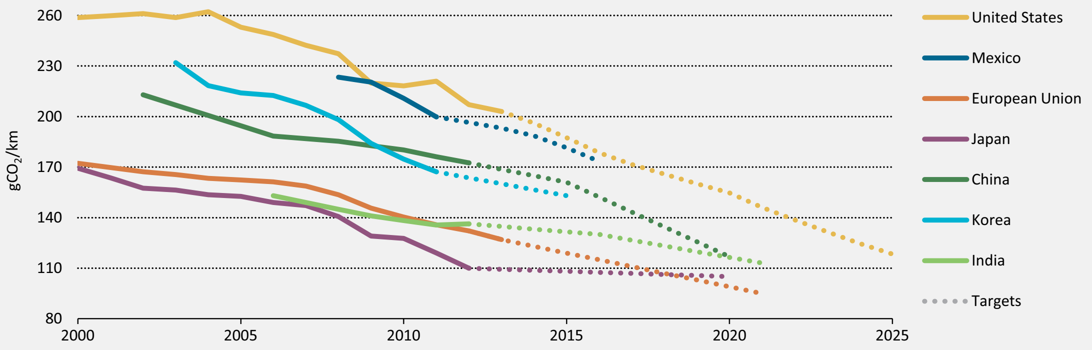
Electrolysis is the most energy-intensive step in production of aluminium. Decarbonisation of the power sector could significantly reduce indirect CO_2 emissions from the aluminium sector.

Activities to develop and commercialise innovative aluminium-based products are gaining relevance through approaches that examine sustainability along the full value chain. These approaches help not only to reduce the environmental impacts of manufacturing but also to maximise sustainability during product use and at its end of life. Industry representatives recently highlighted the importance of full value chain approaches by proposing criteria for a global standard for sustainable aluminium production that would apply to all stages of aluminium production and transformation. The proposal, now open for public consultation, is part of the Aluminium Stewardship Initiative led by the International Union for Conservation of Nature (IUCN, 2014).

Box 6.4 Demand for lighter cars encourages innovation by aluminium and steel sectors

Vehicle GHG emission and fuel efficiency standards have been getting more stringent globally (Figure 6.8) (NHTSA, 2012). Car manufacturers have worked closely with their suppliers to adapt to this changing regulatory landscape, as well as to new consumer expectations. The aluminium and steel industries have been supporting research on reducing the mass of vehicles as a way of lowering fuel consumption and related CO_2 emissions, among other possible measures such as engine downsizing and reducing aerodynamic drag and rolling resistance. A 10% weight reduction generally reduces fuel consumption by 6% to 7% if vehicle performance remains constant and the engine is appropriately resized (NRC, 2013). New steel grades and aluminium alloys, combined with optimised vehicle designs, can achieve significant mass reductions (up to 25% for new steel grades) (FKA, 2006). Car mass can be reduced by using more aluminium. In 1994, Audi started producing the first aluminium-bodied car, which had a body 40% lighter than the steel-bodied version (Audi, 2013). More recently, Ford Motor Company and the US aluminium company Novelis have collaborated in a three-year programme to develop new aluminium alloys that can be delivered in enough volume and that meet automotive body sheet specifications, such as durability, strength, lightness, formability and surface characteristics, and recyclability (Novelis, 2013). As a result, in 2015 Ford Motor Company will start producing a vehicle with an aluminium alloy body that weighs a third of a tonne less than the original model. Efforts to reduce the mass of cars are expected to continue as a response to more stringent fuel economy policies. But the future material mix for cars will depend strongly on the potential to introduce innovative materials at a moderate cost, so that lighter vehicles can remain competitive within their targeted consumer segment.

Figure 6.8 CO_2 emissions standards for light-duty vehicles by region



Notes: gCO_2/km = grammes of CO_2 per kilometre. Enacted and proposed CO_2 emissions standards targets for passenger vehicles shown are normalised to the New European Driving Cycle test. China's reflect gasoline vehicles only. As gasoline in Brazil contains 22% ethanol, data have been converted to gasoline equivalent.

Source: ICCT (International Council on Clean Transportation) (2014), Global Passenger Vehicle Standards (database), www.theicct.org/info-tools/global-passenger-vehicle-standards (accessed 15 January 2015).

Key point *Regional CO_2 emission standards for light-duty vehicles show some degree of convergence towards 2020.*

Measuring low-carbon industrial innovation

Measuring industrial innovation is challenging. It involves monitoring resources dedicated to innovation activities (inputs), resulting developments (outputs) and how these are interrelated (performance, or effectiveness).

- **Input-based indicators** include spending on innovation activities, the number of employees involved, and the number of dedicated laboratory or pilot testing facilities, among others.
- **Output-based indicators** include the number of industrial process concepts developed, the number and size of pilot or demonstration projects, the number of new process technologies licensed or new products patented, commercial-scale capacity additions of an innovative technology, and business value-added gained from a new product, among others.
- **Performance indicators** are difficult to define because of the time lag between innovation activities (inputs) and the results they generate (outputs). An example could be business value-added achieved by introducing a new product in the market over the investment required to develop and commercialise it. Performance indicators are useful to assess the effectiveness of innovation, but their usefulness for cross-sectoral comparative analysis is limited, as they depend on sector-specific characteristics.

Official data are available for some of these indicators, but their limited coverage of countries and time spans undermines their usefulness for comparative analysis (Box 6.5). Input-based data include R&D spending and R&D spending intensity, which is the ratio of R&D spending to total sales or business value-added of a specific sectoral activity.[11] These indicators have a limited scope as they refer only to the R&D phases of innovation process and not to demonstration and deployment. Output-based data include patent counts, patent citations and new products. These also present limitations, as they monitor only the final result and not results at the different stages of the innovation process. Official data provide no information on the performance or efficiency of innovation.

Box 6.5 R&D industrial spending statistics databases and considerations

Comparing official R&D expenditure statistics for industrial sectors can be difficult because countries use different data collection and allocation methodologies. For instance, R&D spending from a diversified company may be applied to the industrial sector corresponding to its main activity. As a result, R&D spending on secondary activity sectors can be underestimated in sectors where a few large companies dominate R&D expenditure. However, some countries allocate R&D investment to each activity sector for their largest companies, or collect R&D data directly on a product field basis. To provide a comprehensive and internationally comparable data series on industrial R&D spending, the OECD developed the Analytical Business Enterprise Research and Development database (ANBERD). ANBERD data may differ significantly from the corresponding official data, as they include estimates (OECD, 2013).

Another database, the European Industrial R&D Investment Scoreboard managed by the European Commission (EC), collects economic and financial data from the 2 000 companies in the world that spend the most on R&D. The usefulness of this database for comparisons among countries is limited by factors such as annual variations in exchange rates, changes from year to year in the sample of companies included, and attribution of R&D spending to the country where a company has its registered office, which may not be always where the actual R&D takes place (EC, 2013a).

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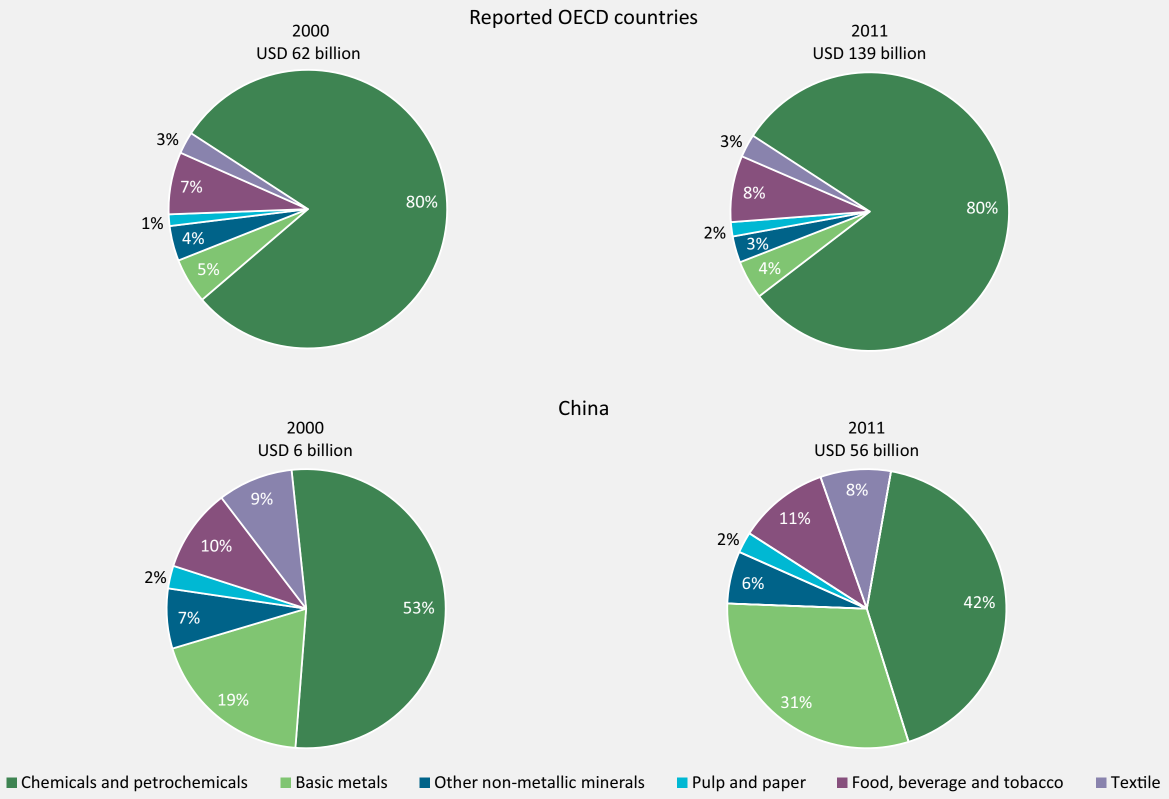
[11] Typically R&D spending intensity provides greater values when referring to business value-added than when it is based on total sector sales.

Measuring sustainability-oriented industrial innovation poses additional challenges, stemming from the difficulty of segregating low-carbon RDD&D from broader industrial innovation: they are often interlinked, with innovation aiming at reducing environmental impacts providing other benefits, and vice versa. Another barrier is that available data on R&D expenditure, energy use and CO_2 emissions are not broken down by technology or process route. More detailed data are necessary so that sustainability-oriented industrial innovation can be measured more accurately.

Despite the limitations of input-based indicators, they do shed some light on how innovation is spread across regions and sectors. In 2011, **business R&D spending** in selected industrial

Figure 6.9 Business R&D spending in selected industrial sectors by region



Notes: OECD excludes Chile, Denmark, Estonia, Greece, Iceland, Ireland, Luxembourg, New Zealand, Sweden, Switzerland and the United Kingdom due to lack of data. In the OECD data series, Israel is excluded in chemicals and petrochemicals, basic metals, other non-metallic minerals, and pulp and paper. Poland, the Slovak Republic, France, Portugal and the Netherlands are included only in reported business R&D expenditure for 2011, due to data availability limitations. 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.

Source: OECD (2014), *The OECD Analytical BERD (ANBERD) Database* (dataset), http://stats.oecd.org/Index.aspx?DataSetCode=ANBERD_REV4.

Key point *R&D spending sectoral mix has remained steady in reported OECD countries, whereas there has been a shift of investments from the chemicals and petrochemicals sector to basic metals in China.*

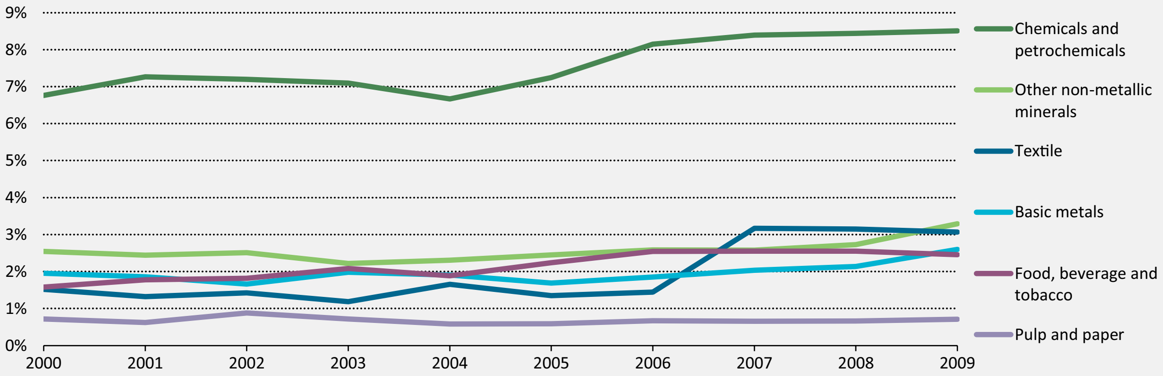
sectors[12] was USD 194 billion[13] in OECD countries and China, a 10% increase in compound annual growth rate (CAGR) since 2000. China experienced the greatest overall growth in industrial R&D expenditure, of 22% CAGR since 2000. In the first half of the 2000-11 period, R&D industrial investment by businesses in OECD America and OECD Asia Oceania grew over three times, almost twice as fast as in the second half of the period (OECD, 2014).

The distribution of business R&D expenditure among the selected industrial sectors is similar throughout OECD countries, with the chemicals and petrochemicals sector standing out as the major investor in innovation (Figure 6.9). The sector's share of industrial R&D spending in 2011 was 86% in OECD American countries and 73% to 77% in OECD Europe and Asia Oceania. The sectoral mix differs in China, where the chemicals and petrochemicals sector still provides the greatest contribution (42%), but the basic metals sector almost reaches a third of the industrial R&D expenditure (31%).

This distribution of R&D investments was stable between 2000 and 2011 in OECD countries, but in China R&D spending shifted by 12% from the chemicals and petrochemicals sector to the basic metals sector. This shift reflects the structural change in China over the period, when crude steel production increased more than fivefold.

Industrial R&D intensity as a share of value-added varies greatly from sector to sector. The chemicals and petrochemicals sector is by far the most R&D-intensive of the selected industrial sectors (Figure 6.10). Some theoretical models suggest that companies in sectors with a high level of product differentiation tend to favour product innovation (Weiss, 2003). As the chemicals and petrochemicals sector covers a wide range of intermediate

Figure 6.10 R&D intensity as a share of value-added by selected industrial sector in reported OECD countries



Notes: R&D intensity trends exclude Chile, Estonia, Luxembourg, New Zealand, Switzerland and Turkey because of lack of data. R&D intensity trends for basic metals and pulp and paper sectors exclude Israel. Because of data limitations, Austria and Denmark are excluded in 2000; Austria in 2001; Australia, Ireland and Portugal in the period 2006-09; Denmark, France, Poland and the United Kingdom in the period 2007-09; Canada in 2000; OECD America countries, Greece, the Netherlands and Sweden in the period 2008-09; and Israel, Germany and Norway in 2009.
Source: OECD (2014), *The OECD Analytical BERD (ANBERD) Database* (dataset), http://stats.oecd.org/Index.aspx?DataSetCode=ANBERD_REV4.

Key point *The chemicals and petrochemicals sector stands out as the most R&D-intensive sector within the selected industrial sectors in reported OECD countries.*

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[12] The term *selected industrial sectors* in this chapter refers to the energy-intensive manufacturing sectors: chemicals and petrochemicals, basic metals, other non-metallic minerals, and pulp and paper; as well as to two non-energy intensive industrial sectors: food, beverage and tobacco and textile. The selected industrial sectors represent almost three-quarters of total industrial energy use.

[13] Measured in terms of purchasing power parity expressed in current prices.

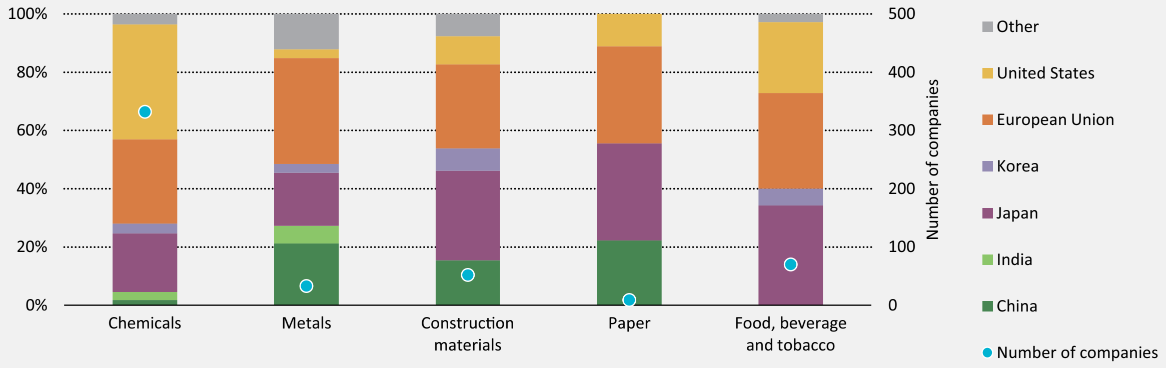
chemical building blocks (e.g. ethylene and propylene), and final products and materials (e.g. pharmaceuticals, rubber, plastics), it has an inherently high product diversity that encourages innovation. The pharmaceutical sub-sector has a high R&D intensity, which pushes up the overall intensity of the chemicals sector.

Industrial innovation efforts need to be considered throughout the process technology chain. Equipment manufacturing sectors (not included in the industrial sectors selected here) tend to have greater R&D investment intensities as a share of sector value-added. This partially explains lower R&D intensity levels observed in the energy-intensive manufacturing sectors, which depend on upstream equipment innovation. For instance, in OECD America and OECD Asia Oceania, the equipment manufacturing sector spent twice as much on R&D on average as the chemicals and petrochemicals sector, as a share of sector value-added, in the period 2000-07 (OECD, 2014).

Industrial R&D intensity grew in OECD countries in the period 2000-09 despite the global economic crisis in 2008 and 2009. The textile sector (8% CAGR) and the food, beverage and tobacco sector (5% CAGR) experienced the greatest increase among the selected industrial sectors. R&D intensity grew by 3% CAGR in the other sectors, with the exception of the pulp and paper sector, where it remained steady (OECD, 2014). Drawing robust conclusions from these trends is difficult because data are not available for all OECD countries for every year. Some countries for which data are missing play a significant global role in the selected industrial sector. For example, Canada and the United States account for almost 22% of global paper production but have been excluded in the pulp and paper sector R&D intensity average for 2007-09 because of lack of data. This can lead to an underestimation of the real innovation intensity level in the sector in that time frame.

On a company by company basis, of the 2 000 companies in the world that spend the most on R&D, only 496 belong to the selected industrial sectors[14] (EC, 2013b). Among this group, 332 companies (67%) belong to the chemicals and petrochemicals sector, 70 to the food, beverage and tobacco sector (14%) and 52 to the construction materials sector (10%).

Figure 6.11 Regional distribution of companies that spend the most on R&D, by selected industrial sector, 2012



Note: The textile sector is embedded within the personal goods sector in the EC database (2013b), thus textile companies are not included within the selected industrial sectors.
Source: EC (2013b), *The 2013 EU Industrial R&D Investment Scoreboard* (dataset), EC, Brussels.

Key point *Almost two-thirds of the companies within the top 2000 world R&D spending ranking are located in Europe and the United States.*

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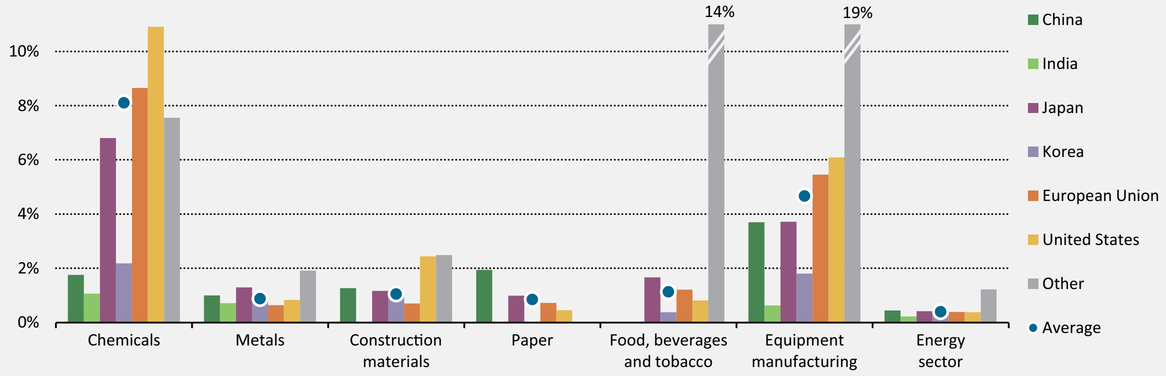
[14] Selected industrial sectors exclude textiles when referring to the top 2 000 world companies R&D spending ranking database since textiles companies are embedded within the personal goods category, and are not a stand-alone sector.

Of the companies within the selected industrial sectors that spend the most on innovation, more than four-fifths are in the United States (32%), Europe (30%) and Japan (22%). However, this regional distribution is not observed in all of the selected industrial sectors; in the basic metals, construction materials, and paper sectors, other countries, especially China, have significant shares.

Within the 2 000 companies that invest the most in innovation, R&D spending patterns differ from sector to sector. In terms of R&D spending as a share of sales, chemical companies spend five times as much as companies in other sectors globally, six times as much in Europe and the United States, and two to four times as much in India, Japan and Korea. R&D intensity among China's industrial sectors is more homogeneous.

Figure 6.12 R&D intensity of companies within top 2 000 world ranking by sector and region, 2012



Note: The textile sector is embedded within the personal goods sector in the EC database (2013b); thus textile companies are not included within the displayed sectors.
Source: EC (2013b), *The 2013 EU Industrial R&D Investment Scoreboard* (dataset), EC, Brussels.

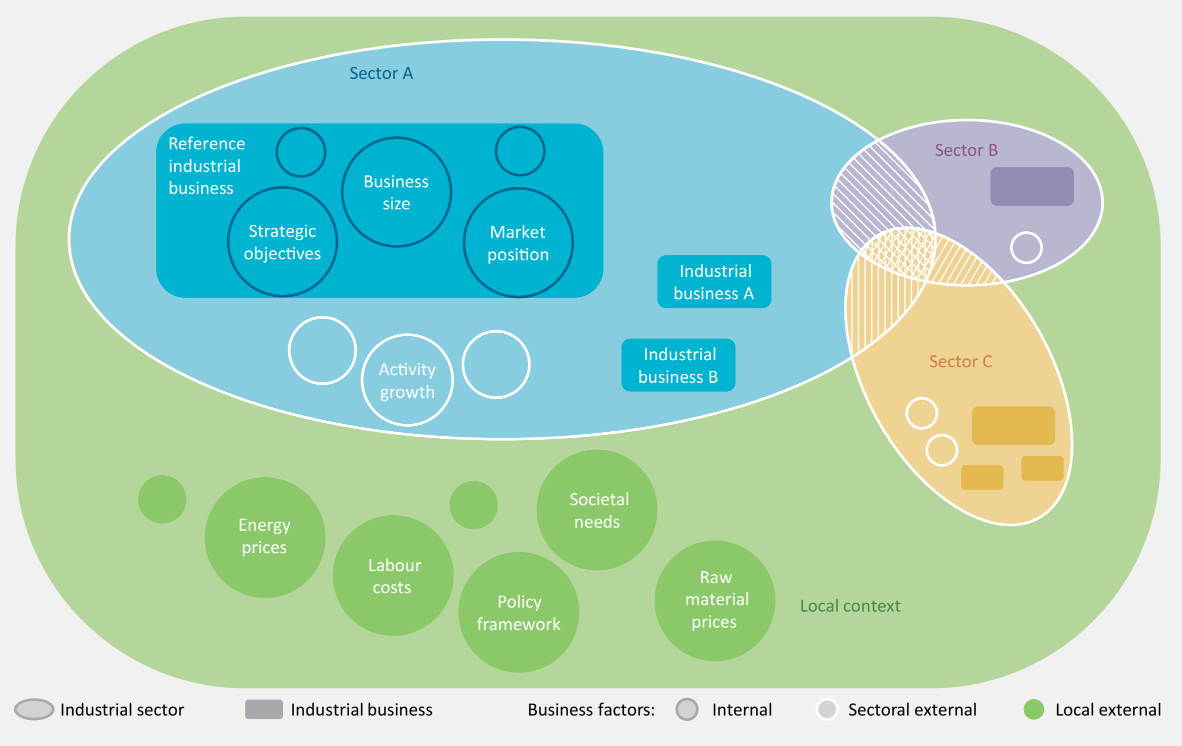
Key point *Within the 2 000 companies in the world that spend the most on R&D as a share of sales, chemical businesses invest over five times as much as companies in other sectors.*

Incentives for industrial innovation

For industry, innovation is a crucial way of improving competitiveness, safety, reliability and environmental sustainability. Prioritising resources allocated to innovation in each of these areas is a complex process where many factors are involved. But industrial technology breakthroughs are seldom achieved in isolation: researchers and developers are influenced by incentives and constraints (Luiten and Blok, 2001). From a business perspective, incentives for broader industrial innovation and for sustainability-oriented innovation can be grouped in two categories:

- **Internal business factors** that are specific to each company, such as corporate strategic objectives, company size or relative position in a specific market.
- **External business factors** that affect a company's interaction with other parties, local markets and the policy environment, such as energy prices, costs of materials and labour, policy frameworks, new societal needs, existing connections with other sectors through product value chains, and the potential to enter other established value chains.

Figure 6.13 Interactions among incentives for industrial innovation



Key point *Industrial innovation is incentivised by a complex interaction among internal and external business factors.*

Low-carbon industrial innovation is typically believed to be a reaction to external business factors such as high energy prices and national policies aimed at limiting industrial energy use and related CO_2 and pollutant emissions. But research on the development and deployment of efficient industrial technologies in the paper and steel sectors shows that internal business factors tend to motivate R&D, while external business factors tend to promote further technology improvements during deployment (Luiten and Blok, 2001, 2002). These case studies concluded, however, that the balance between internal and external factors cannot be generalised, and needs to be understood case by case to optimise support for RDD&D.

A wide survey of manufacturing companies in the United Kingdom in 2006 showed that company-level aspects contribute significantly to the probability that a business will pursue innovation. Internal business factors such as the existence of an R&D strategy and large company size, as well as external business factors such as interactions with other companies, including equipment suppliers and other sectors, were found to increase the likelihood of developing or introducing new processes or technologies at the company level (Reichstein and Salter, 2006).

Broader innovation and sustainability-oriented innovation can be interlinked – boosting productivity can increase energy efficiency, for example, and vice versa – so it is difficult to identify specific incentives for each kind of innovation (Box 6.6). It is advisable to identify all benefits offered by each new process or technology, from improved sustainability to enhanced production, to avoid missing cost-effective opportunities to reduce environmental impacts.

Governments' sustainability targets and related policies can also encourage innovation that reduces environmental impacts of industrial activities. But the impact of policies will differ from sector to sector, as it depends on the ability of each sector to adapt to environmental targets. In some manufacturing processes, for example, process emissions generated through the chemical decomposition of certain raw materials cannot be reduced unless an adequate alternative feedstock is found or emissions are captured.

Box 6.6

Wet kiln to dry kiln process transition in the Brazilian cement sector

After the petroleum crisis in the 1970s unexpectedly increased oil prices, the Brazilian government signed a protocol with the cement industry in 1979 to drastically reduce the use of fuel oil in the sector as fast as possible.

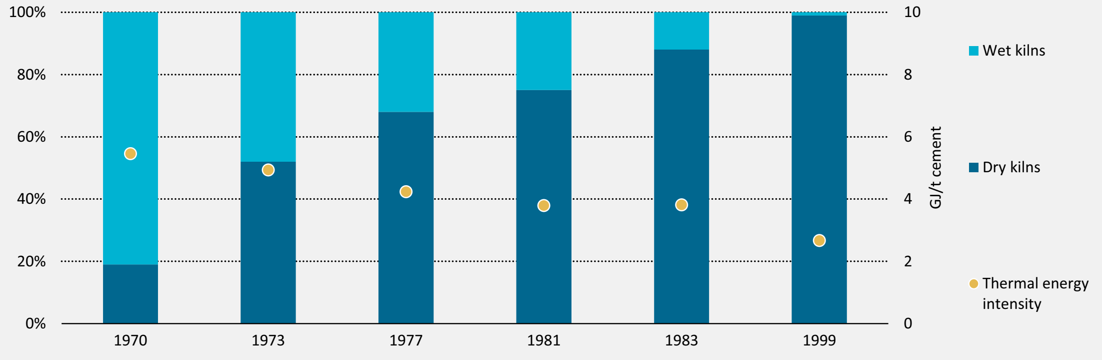
The government introduced tax incentives and funding programmes to facilitate industrial process adaptations and the purchase of required equipment, as well as technical and financial support for research on decreasing CO_2 emissions through fuel substitution. The cement industry committed to reducing energy use in cement production by converting wet kiln systems to semi-dry processes and dry processes with lower thermal energy requirements, and by increasing clinker substitution with materials such as fly ash (a waste stream from coal power plants) and blast furnace slag from national steel production.

By 1999, the share of wet process kilns had fallen from 44% to 1%. This reduced the vulnerability of the Brazilian cement industry to energy price volatility, helping the industry to maintain a competitive position.

The signature of the protocol encouraged other practices that reduced energy use and the CO_2 footprint of cement making in Brazil. Average thermal energy intensity per tonne of cement fell from 3.9 GJ/t of cement in 1979 to 2.7 GJ/t of cement in 1999 (Figure 6.14); current levels are 2.3 GJ/t of cement. By 1999, the use of clinker substitutes increased from 11% to 27% (current level reaches 33%). Over 70% of the country's integrated sites are licensed to co-process alternative fuels.

Figure 6.14

Cement kiln process transition and thermal energy intensity impact in Brazil



Source: SNIC (2014), personal communication.

Key point *A significant shift towards dry kiln processes helped to halve thermal energy intensity in Brazil's cement sector.*

Source: SNIC (Sindicato Nacional da Industria do Cimento) and ABCP (Associaçao Brasilieira de Cimento Portland) (2013), "The journey to a low-carbon world", *World Cement*, Palladian Publications, Farnham, Surrey, June.

Policy mechanisms have different impacts depending on the stage within the innovation process at which they are applied. For instance, several studies show that instruments such as carbon pricing are more likely to trigger incremental energy savings and deployment of BATs rather than foster low-carbon industrial breakthroughs (Nemet, 2009; Smith, 2009), mainly because of uncertainties about future carbon pricing levels and international implementation. A more recent survey in Brazil, China, India, Russia, South Africa and 26 OECD countries concluded that long-term policies designed to commercialise low-carbon innovations, through direct or indirect support for specific or more generic low-carbon technologies (including support for entrepreneurship), are more successful than shorter-term fiscal policies such as tax incentives and rebates (Criscuolo and Menon, 2013).

Challenges for industrial innovation

Industrial innovation faces different interlinked challenges. They fall into three main groups: an uncertain economic and policy outlook that can make it difficult to justify investment in innovation, the need to manage risk, and the need to balance collaboration with protection of knowledge. The relative importance of these challenges depends on the phase within the RDD&D process at which the technology or process stands. For instance, fundamental research and laboratory-scale tests tend to be less capital-intensive but they typically involve more incertitude as the technology principles have not been proven yet. Throughout these initial phases of RDD&D, cross-sectoral international collaboration and information-sharing may be critical for a project's success, as they can accelerate the research learning process and reduce associated incertitude levels. By contrast, technological success is more likely when scaling up to the demonstration phase. But building and operating a demonstration plant can be significantly capital-intensive, so a healthy economic environment and robust risk assessment become more important.

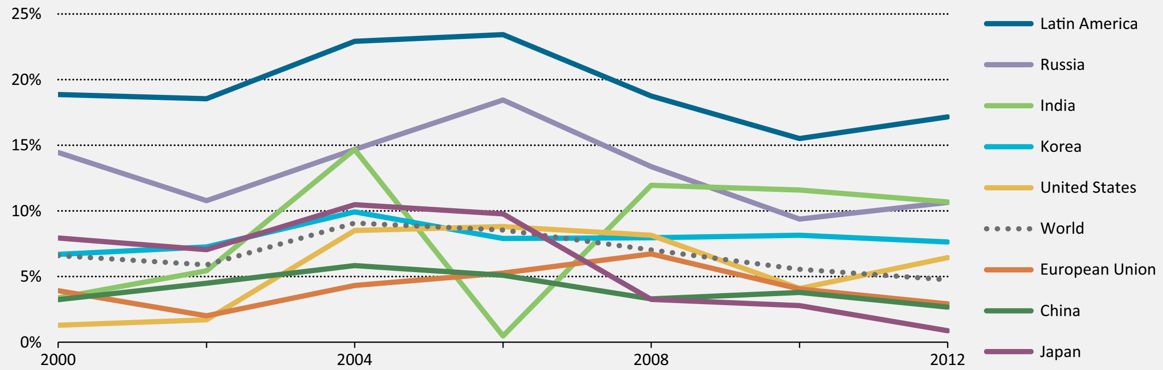
Low-carbon industrial innovation can face additional challenges, such as the difficulty of penetrating a market dominated by a small number of widely used process technologies. This is especially relevant when environmental benefits are undervalued, when growth prospects are only moderate, or where it is difficult to track environmental impacts along the value chain, as in highly diversified markets (e.g. multiple production routes and final uses for plastic-based products). Technologies that require new infrastructure – such as the transport and storage facilities needed for CCS – face particular hurdles. In addition, public and political support varies regionally for low-carbon technologies that are still not commercially proven.

Uncertain economic and policy outlook

Industrial RDD&D often requires significant up-front expenditure long before revenue flows, so it needs a healthy economic environment to thrive. The capital required also increases from phase to phase of the RDD&D process, so commercial activity and operating margins need to be predictable in the long term if industries are to invest in innovation.

Operating margins are influenced by several factors, such as product demand, energy prices, feedstock availability, labour and environmental compliance costs, and the tradability of a specific material. Fluctuating margins in the iron and steel sector illustrate these influences. The global net operating margin, as a share of the sector's sales, has fallen by 3% CAGR since 2000 (IHS, 2014). Within this global average, regional variations are marked. The net operating margin in Japan fell by 17% CAGR, mainly because of increasing energy costs, but rose by 14% CAGR in the United States and 10% CAGR in India. Net operating margins have fallen significantly in China since 2004 (by 9% CAGR) mainly because overcapacity increased when growth in demand for crude steel slowed earlier than expected (Figure 6.15).

Figure 6.15 Net operating margins in the iron and steel sector by region



Notes: Net operating margin values from 2014 onward are estimates. China excludes Hong Kong.
Source: IHS (IHS World Industry Service) (2014), dataset provided by IHS.

Key point *Globally, net operating margins in the iron and steel sector have decreased 3% CAGR since 2000.*

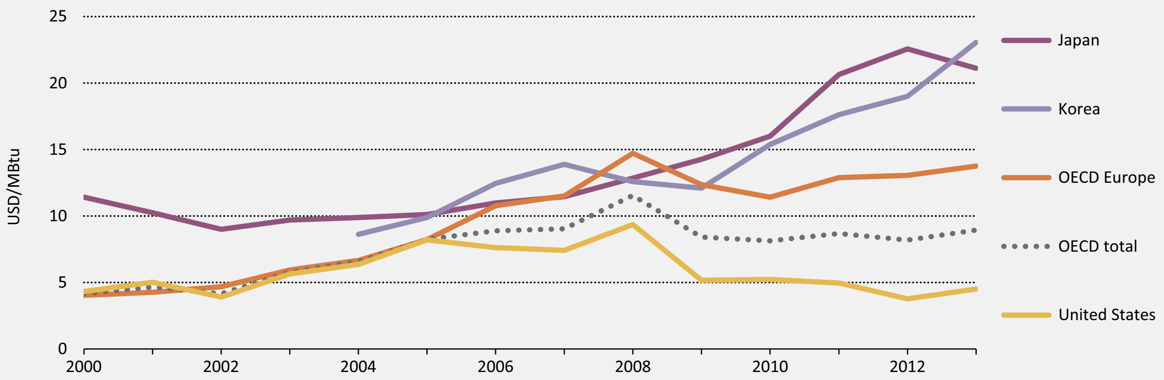
In OECD countries, net operating margins in the iron and steel sector fell by 6% CAGR in average between 2000 and 2009, but R&D intensity as a share of sales grew by 3% CAGR (Figure 6.15), showing that these countries have been giving innovation higher and higher priority.

Industries in regions with high or volatile **energy prices** may find it more attractive to invest in the short and medium term in energy efficiency measures to reduce energy costs and exposure to volatile energy markets. Conversely, investing in innovation tends to have longer-term economic benefits. Companies need to balance these considerations when deciding how to spend their limited investment capital.

Natural gas price trends illustrate the conundrum that industries face. While natural gas prices in key countries in the OECD Asia Oceania region have increased – by 6% CAGR in Japan since 2000 and by 10% CAGR in Korea since 2004 – R&D intensity in the region increased around 3% CAGR in the majority of selected industrial sectors in the period 2000-09. This shows that despite economic pressures, a sector can deliberately make the strategic decision to invest in innovation. Such efforts can be reinforced by adequate risk management tools and mechanisms to balance the sharing and protection of knowledge and experience.

Prospects for **material production demand** also play a considerable role in determining a sector's capital investment needs for additional capacity, and opportunities to deploy innovative low-carbon technologies. A survey of companies in Brazil, China, India, Russia, South Africa and 26 OECD countries concluded that the prospect of rising market demand significantly increased investment in low-carbon innovation (Criscuolo and Menon, 2013). Slowing growth in materials demand can also promote low-carbon innovation, however, by encouraging companies to develop greater added-value materials or more diversified final products that can help them regain market share.

Figure 6.16 Natural gas price for industry by region



Notes: MBtu = million British thermal units. Natural gas price value for Japan in 2008 is interpolated because of missing data point.

Key point *The increasing regional divergence of natural gas prices over the last decade has set up a new framework for prioritising sustainability within industrial innovation.*

Public and private investment in low-carbon technologies can be hard to justify if there is uncertainty about when and whether investments can be recovered. Unless **penalties on carbon-intensive production** rise considerably, many innovative technologies mentioned in this chapter will struggle to attract investment. This is especially true for processes that involve CCS, for which it is difficult to find early markets that are willing to pay a sufficient premium for “green” materials and products.

Even where penalties for CO_2 emissions do exist, they are regional rather than global and are likely to remain at different levels in different regions. Most sectors discussed here are exposed to international trade, so a carbon pricing policy aimed at encouraging producers to invest in innovation may instead lead them to relocate production. In Europe, cement imports could become more attractive than domestic cement at EU carbon prices of EUR 15/tCO_2 to EUR 20/tCO_2 in some countries, which is below the cost of emissions reduction through CCS (Climate Strategies, 2014).

Without a clear idea of when climate policies might make low-carbon production globally competitive and widespread, companies will find it difficult to justify investing in pilot and demonstration projects in the near term. Furthermore, several governments have fully or partly exempted trade-exposed sectors from carbon pricing (e.g. by allocating so-called free allowances). This prevents CO_2 pollution costs from being passed on to consumers, and thus fails to encourage consumers to reduce their carbon footprints. Such exemptions may further diminish incentives for radical innovation if employing new technologies threatens entitlement to free allowances.

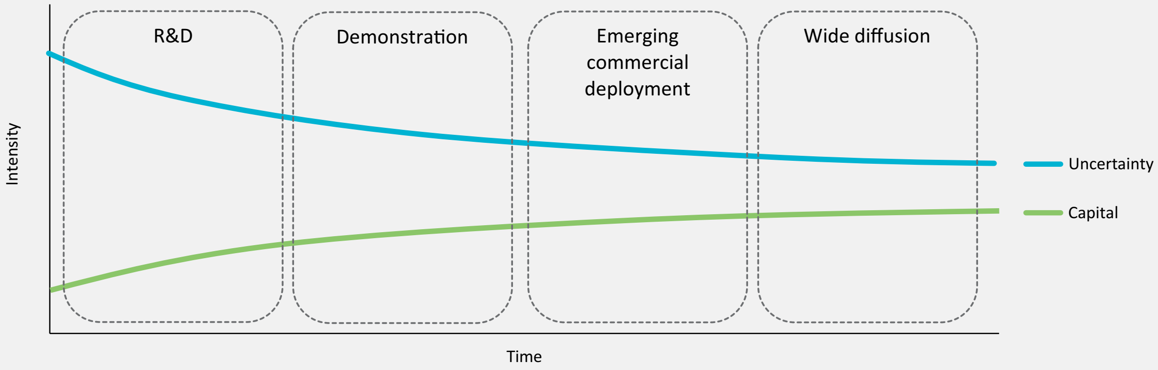
Managing associated innovation risk

Risk is inherent to innovation projects because they aim to develop and deploy completely new processes or products. Thus risk management becomes critical to make RDD&D projects viable. Final decisions on investment depend on many factors, but two stand out: uncertainty intensity and capital intensity.

Investors have different levels of risk tolerance and perception throughout the different phases of the RDD&D process. Financing early phases of research tends to be more uncertainty-intensive, with less chance that the estimated return on investment is met because technology performance or product benefits are yet to be proven. The design and development phase builds on successful results from previous research activities, lowering the level of uncertainty when performing relevant investment risk assessments. Finally, the commercial demonstration stage, although characterised by greater capital intensity, has a more manageable risk because prior pilot-scale trials have provided a basis for considerable confidence in the new technology or product benefits.

While uncertainty intensity decreases as RDD&D advances, capital intensity tends to increase, mostly because of the gradual process of scaling up. A decision to invest in innovation hinges on what balance between uncertainty intensity and capital intensity the investor can accept. Venture funds tend to tolerate more risk, while more traditional investors may only accept more moderate risk.

Figure 6.17 Risk-associated factors along the innovation process in energy-intensive industries



Note: Only illustrative; displayed variables are not drawn to scale.

Key point *Uncertainty and capital intensities follow opposing trends along the industrial innovation process.*

Several risk-mitigating mechanisms can help to promote investment in low-carbon innovation by providing funding or preferential loans, and/or by leveraging investments from other sources. These mechanisms can focus on one or several stages of the RDD&D process. Some cross-sectoral examples:[15]

- **New Entrants' Reserve (NER) 300** is a European programme that funds the demonstration of innovative renewable energy technology and CCS projects. The programme uses funding raised through the sale of 300 million emission allowances from the NER to the third phase of the European Union Emissions Trading System (EU ETS) through two calls for projects, in December 2012 and July 2014 (EC, 2010). Project selection criteria included minimum size thresholds for each selected technology, a near-term expected commissioning date, obtaining required national permits to ensure start-up, and a binding commitment to pursue knowledge sharing. CCS projects were required to cover the full chain of CO_2 capture, transport and storage. No industrial CCS projects were

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[15] This section presents some examples of industrial innovation risk-mitigating mechanisms. The list is not intended to be exhaustive.

submitted to this call. In the second call, grants totalling EUR 1 billion were awarded, which are estimated to have leveraged EUR 860 million from private sources (EC, 2014a; White Rose Carbon Capture and Sequestration Project, 2014). NER 400, the successor programme for NER 300, will have a wider scope, including low-carbon innovative industrial technologies (European Council, 2014).

- **Horizon 2020 (H2020)** is the largest European RDD&D programme to date, offering almost EUR 80 billion over the period 2014 to 2020. The funding can be provided in the form of grants, prizes or procurement (i.e. supply of assets, execution of work or provision of services). It is expected to leverage additional public and private investments, and bring together scientists and industry within Europe and from around the world (EC, 2014c; EC, 2014h). Within one of the three programme pillars, Societal Challenges, RDD&D activities on energy-related industrial innovation are mainly covered by two areas: secure, clean and efficient energy; and climate action, environment, resource efficiency and raw materials. These account for around EUR 9 billion (EC, 2014c). H2020 includes an indicative budget of EUR 4 million to EUR 9 million per project to enable decarbonisation of fossil fuel-based power generation and energy-intensive industry through CCS (EC, 2014b).
- The **Advanced Research Projects Agency (ARPA-E)** was established in 2007 in the United States to support financially and technically the research, development and demonstration of potential breakthrough low-carbon technologies. Programmes supported by ARPA-E cover areas related to energy-intensive industrial sectors such as developing alternative materials and new control systems, improving biochemical processes, and advancing cost-effective thermal storage and CCS technologies. As of April 2014, 85 projects had been awarded a total of about USD 230 million in these areas.[16] In fiscal year 2013, ARPA-E funded projects for a total of USD 102 million, of which USD 32 million was allocated to projects developing cost-effective energy efficiency manufacturing techniques for processing and recycling lightweight metals (US DOE, 2014).
- In China, the scope of the **National Science & Technology Support Programme** includes financial support for developing low-carbon industrial process technologies and related equipment, as well as sustainable materials. The central government's financial support to this programme was USD 2.7 billion in 2012 and leveraged over USD 43 billion from private investment, regional government investment and other financing channels (MOST, 2014).

Some low-carbon innovation risk-mitigating mechanisms target specific industrial sectors:

- **Investments in Forest Industry Transformation (IFIT)** is a programme created in 2010 and funded by the government of Canada to improve economic competitiveness and environmental sustainability by supporting the deployment of innovative “first-in-kind” forestry technologies. The programme provides non-repayable contributions up to 50% of the cost of pilot or commercial-scale projects. Eight of the 14 projects supported to date correspond to world-leading technologies. IFIT has been allocated about USD 81 million (CAD 90.4 million) over the next four years (NRCAN, 2014).
- Support from the European **Research Fund for Coal and Steel (RFCS)** includes projects that aim to reduce CO_2 emissions. In 2011, EUR 44.5 million was provided to steel-related projects. Between 2003 and 2010, a cumulative benefit of about EUR 100 million per year was expected, from an initial investment of EUR 53 million per year (EC, 2014b).

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[16] Programmes included are: Innovative Materials and Processes for Advanced Carbon Capture (IMPACCT), Plants Engineered to Replace Oil (PETRO), High Energy Advanced Thermal Storage (HEATS), Rare Earth Alternatives in Critical Technologies (REACT), Modern Electro/Thermochemical Advancements for Light-Metal Systems (METALS) and Strategies for Wide Bandgap, Inexpensive Transistors for Controlling High Efficiency Systems (SWITCHES).

Balancing collaboration and knowledge protection

Enlarging collaborative relationships can accelerate innovation while increasing the chances that a technology will be adopted more widely, by involving a greater number of interested parties. Competition can also boost innovation, because companies know that introducing a new development in the market can give them a commercial advantage. But collaboration and competition inevitably run into conflict. So maximising the power of each to promote innovation involves finding the best balance between collaboration at different levels (e.g. interdisciplinary, international, cross-sectoral, across the product value chain) and protecting IP.

Sectoral and cross-sectoral private collaboration, as well as PPPs, can help to solve this challenge. They can also help to mitigate other barriers to new industrial developments, such as high risk, by establishing investment-sharing mechanisms.

Involving stakeholders from the whole product value chain facilitates the development of integrated low-carbon solutions (Box 6.7). PPPs have greater added value because they integrate expertise from businesses and policy makers. They also enable better alignment of public and private sustainability goals and more effective support for innovation.

Box 6.7

Fostering co-operation by managing competition: *The Two Team Project*

In 2013, the Confederation of European Paper Industries (CEPI) led an open competition initiative to identify technologies that could significantly reduce the carbon footprint of the pulp and paper industry. Two teams of researchers, scientists, manufacturers, suppliers and other industrial representatives worked together to establish a common knowledge basis, and then competed to find innovative ways to improve the environmental sustainability of the sector. Creativity and diversity of approaches were maximised by establishing a robust legal framework to encourage team members and participants around the world to provide ideas through a dedicated website. Team members and CEPI partners signed non-disclosure agreements and agreed on assignment of licenses of IP rights for further development of the resulting concepts. Collaboration with national experts and sector representatives enriched the collective knowledge of the teams. The project maximised the level of co-operation by focusing on pre-competitive concepts. The teams came up with eight innovative concepts. Some described new technologies; others provided low-carbon ways to adapt existing capacity through retrofits, or to improve energy efficiency significantly by integrating existing technologies. A key finding from the project was that to promote innovation, it is vital to start assessing a material's energy intensity based on the value it adds to society rather than just measuring production.

Source: CEPI (Confederation of European Paper Industries) (2013), *The Two Team Project*, CEPI, Brussels.

Regional PPPs may face limitations because many private companies operate at a global level while governments have national or regional competencies. So even if a PPP links licensing and IP rights to the region where the partnership operates, knowledge could leak outside the region through global companies. At the sector level, competitiveness can also be limited because PPPs typically involve high transaction costs that only companies of a certain size are able to meet (IISD, 2011).

Most PPPs have focused on public infrastructure (IISD, 2011), but they are increasingly addressing other societal needs, including environmental sustainability. PPPs and private collaborative mechanisms can be established nationally, regionally or even more widely.

Cross-sectoral and sectoral private platforms and PPPs that aim to accelerate the progress and impact of low-carbon innovation include:[17]

- **Sustainable Process Industry Through Resource and Energy Efficiency (SPIRE)** is a cross-sectoral PPP co-funded by H2020 that aims to develop new technologies and solutions for the process industry. By sharing energy solutions among several sectors, it aims to reduce fossil fuel energy intensity by up to 30% and the use of non-renewable raw materials by up to 20%, and has an indicative budget of EUR 900 million for the period 2014-20 (EC, 2014d; SPIRE, 2013). The partnership includes the cement, ceramics, chemicals engineering, minerals and ores, non-ferrous metals, steel, and water sectors. It was established by a contractual arrangement between the EC and private stakeholders organised under an association called A.SPIRE. When technologies have been successfully demonstrated, they will be deployed by industry (SPIRE, 2013).
- **FPInnovations** is a PPP created in 2007 to improve profitability, performance, sustainability and value creation in the Canadian forest sector by aligning government and private objectives, and incorporates collaboration with universities (FPInnovations, 2011). It has become the world's largest PPP focusing on forest sector innovation (FPAC, 2014) with a reference budget of almost USD 90 million (CAD 100 million) and around 550 staff. The organisation measures its performance by assessing returns on innovation investment in terms of outcomes such as new products and services introduced in the market (FPInnovations, 2011).
- The Japanese **COURSE 50** programme runs in two phases. The first phase is divided into step 1 (2008-12) and step 2 (2013-17). New Energy and Industrial Technology Development Organisation (NEDO) funded Phase I step 1 with a budget of about USD 92 million (JPY 10 billion). The programme brings together several steel and engineering companies, as well as universities and research institutions (Tonomura, 2013).
- Different sectoral **European Technology Platforms (ETPs)** are intended to foster innovation in areas such as chemical, steel and textile industries; advanced engineering materials; and competitive and sustainable manufacturing. The platforms include producers, stakeholders from different stages of materials value chains, research institutes, major European universities, and representatives from the EC and national governments. They are expected to focus now on ways of commercialising innovative technologies (EC, 2014d; EC, 2014e; EC, 2014f; EC, 2014g).

Governments tend to focus on industries that are the most important in their countries and in which they have most experience (OECD and World Bank, 2014). Consequently, co-operation among countries and regions is essential to reduce emissions globally. For instance, in 2013 a collaborative initiative between governments and private stakeholders from Japan and India identified low-carbon technologies that could save 13 $MtCO_2$ per year in India's iron and steel sector (JISF, 2014).

Recommended actions for the near term

To guide industrial innovation towards sustainability, governments and private stakeholders need to assess industrial growth not in terms of tonnes of material produced but in terms of how much value products add to society. This major change requires using new methods

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[17] This section presents some examples of collaborative mechanisms to foster low-carbon industrial innovation. The list is not intended to be exhaustive.

to gain a full understanding of sustainability impacts throughout value chains, as well as identifying alternative product diversification routes.

Energy efficiency improvements and wider adoption of BATs in new production capacity additions hold significant energy savings potential in the near and medium term. Policy action in the form of incentives, standards and removal of energy price subsidies is needed to unlock this potential.

Public and private collaboration is crucial over the next decade to develop and demonstrate a portfolio of sustainable process technologies and products so that enough viable options are ready for deployment by 2030 to support efforts to reduce carbon emissions to 2DS levels. The prevalence of CCS processes among innovative technologies in almost all sectors discussed here shows that they should be given higher priority in industrial and public RDD&D efforts.

As reducing CO_2 emissions in the industrial sector will require substantial investment, governments should implement stable, long-term low-carbon strategies that make it worthwhile for industry to reduce environmental impacts. Such strategies would support progress on energy efficiency in existing technologies and the development and demonstration of other innovative low-carbon technologies. International co-operation to support government strategies – such as long-term, legally binding GHG reduction targets and stable, continuous CO_2 pricing mechanisms – will encourage businesses to invest in sustainable alternatives.

In cases where trade exposure constrains their ability to establish carbon pricing mechanisms, governments will need to take greater ownership of this process by implementing effective investment risk-mitigating mechanisms that stimulate innovation and are linked to long-term low-carbon strategies. Through these mechanisms, public investment should unlock private finance in areas with great potential for sustainability returns but a low likelihood for independent private sector investment. Such financial support should be combined with policy commitments to ensure commercial use of the technology soon after demonstration, with targeted support to create initial niche markets where necessary. Such an approach is especially relevant in regions with stable or moderate industrial activity growth prospects, where local markets do not provide incentives for private investors. For CCS, CO_2 purchase commitments have been suggested as a tool for early market creation, alongside instruments that pass carbon price signals on to consumers (IEA, 2014; Bennett and Heidug, 2015).

Several approaches can maximise the sustainability impact of investment risk-mitigating mechanisms:

- **Developing transparent selection criteria** to assess project candidatures and minimise bureaucracy.
- **Targeting innovation processes** instead of innovation providers. Governments can maintain greater ownership of the mechanism impact by mitigating investment risks in specific sustainable process technologies or products.
- **Balancing a wide scope without losing effectiveness** to direct resources towards industrial innovation streams with greater potential for sustainability improvements, while maintaining some diversity in low-carbon routes. This is necessary since it is unlikely that all innovative routes within long-term low-carbon strategies will reach commercialisation. An adequate balance can be ensured by selecting a minimum number of projects for specific innovation routes.

- **Creating dynamic and results-oriented mechanisms** to set intermediate technical milestones along the innovation process, the completion of which unlocks shares of total allocated financial support, reduces the risk associated with initial capital investment and maintains a better cash flow for investors along the innovation cycle. Financial support allocations could vary along the innovation process cycle as uncertainty decreases.
- **Targeting a wide deployment** of developed and/or demonstrated process technologies or products, by selecting projects linked with technology deployment and transfer.

Governments and industry need to align their sustainable strategic objectives and create relevant co-operative frameworks that help industry maintain competitive advantages while maximising the impact of low-carbon innovation through international and cross-sectoral collaboration. Cross-sectoral PPPs can become win-win solutions to design and deploy sustainable, integrated solutions that minimise carbon emissions along product value chains while also identifying business opportunities. PPPs' contribution in driving industrial innovation towards sustainability can be maximised through:

- **Clear objectives** that reflect a long-term vision and members' engagement.
- **A systemic approach,** through multi-sectoral collaboration along the product value chain to foster integrated solutions to improve existing product life cycles and to explore alternative ones. Collaboration with research institutions and academia can be highly valuable at the R&D phases. Efforts should be made to include both large corporations and small- and medium-sized enterprises to ensure that companies with more limited resources can participate.
- **A broad international range of engaged public and private partners** increases the potential for wide deployment of sustainable innovations while helping to resolve competitiveness issues.
- **Robust legal protection of proprietary knowledge** encourages stakeholders to join partnerships. In turn, this lowers risk levels, promotes creativity, improves quality of designed solutions, accelerates technology learning processes, and enlarges deployment potential. Once a certain level of deployment has been reached, new agreements on licensing and technology transfer can be considered.
- **Results-oriented partnerships** with continuous self-evaluation to enable learning from both successes and failures while maintaining good progress. Functional assessments need to track partnerships' characteristics such as sectoral and international diversity and partners' engagement.

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Chapter 7

Low-Carbon Innovation in Emerging Economies

In the 2°C Scenario (2DS), emerging economies account for the bulk of carbon dioxide (CO_2) emissions avoided – or, without a shift to low-carbon energy technologies, the bulk of rapidly rising emissions. With rapidly growing demand for energy and related infrastructure, these countries have an opportunity to lead the low-carbon revolution.

Key findings

- ***The need to expand infrastructure gives emerging economies a distinct opportunity to reduce or eliminate CO_2 emissions.*** *During build-out, these countries can use a systems approach to apply best available technologies (BATs), improve energy efficiency and integrate variable renewable energy sources (VREs).*
- ***In recent years, emerging economies have shown the greatest gains in low-carbon technology deployment.*** *After 2020, non-member economies will need to overtake countries belonging to the Organisation for Economic Co-operation and Development (OECD) in annual solar photovoltaic (PV) or wind deployment.*
- ***The 2DS projects that VREs will account for 27% of generation in 2050 – with 51% of the growth in emerging economies.*** *China, India and Brazil are aggressively advancing across all stages of renewable energy innovation, particularly in the areas of wind, solar PV and biofuels. China is the current global market leader for wind and PV deployments.*
- ***At present, emerging economies acquire low-carbon technologies primarily by importing innovation; domestic innovation is increasing, and shows marked benefits locally and for South-South technology flows.*** *The emerging economies' overall share of global research, development, demonstration and deployment (RDD&D) is rising with China alone accounting for 21% of global renewable energy investment in 2013. But global patent data indicate that innovation remains concentrated in a few OECD countries.*
- ***Setting low-carbon technology priorities, aligning RDD&D budgets, and establishing sound policy frameworks are critical to stimulating domestic and international activity towards the 2DS for emerging economies.*** *Strengthening local skills (both technical and non-technical) is also vital; a vibrant manufacturing and design sector underpins local innovation and enables countries to meet demand for technologies and related services.*
- ***An important role for OECD countries is to engage actively in emerging economy low-carbon initiatives.*** *OECD countries can gain opportunities domestically and internationally by focusing the design of their domestic RDD&D to take into account applications and needs of emerging economies, offering benefits for both the suppliers and recipients of technologies.*

Opportunities for policy action

- *To realise the energy system transformation outlined in the 2DS, governments should identify priority technologies that suit their national objectives and address currently unmet needs in both emerging and developing countries.*
- *Opening markets to low-carbon technologies developed elsewhere (adopt/adapt) and strengthening domestic capacity across the innovation chain (i.e. in all stages of RDD&D) would give emerging economies a broader suite of options to successfully deploy cost-effective solutions while working to develop their own technologies.*
- *Taking steps to eliminate barriers to trade and investment can have dual benefits for emerging economies: it typically increases the openness to imported technologies and tends to accelerate domestic innovation.*
- *Strengthening local technological capabilities to adopt/adapt imported technologies and to innovate domestically can be achieved through various means, including education and workforce training, international co-operative RDD&D programmes, public-private partnerships, and knowledge diffusion.*
- *Local environments that actively promote low-carbon technologies, particularly by implementing policies to create market demand, are essential to support clean technology firms, especially small and medium-sized enterprises (SMEs) that have a critical role in the innovation process.*
- *Governments in emerging economies need to strengthen regulatory (including for intellectual property rights) and finance frameworks to reduce risks; this will help bring down the financing costs associated with capital-intensive low-carbon investments.*
- *OECD member country governments should share knowledge and experience (both technical and non-technical), and collaborate closely on initiatives to support, enhance and strengthen emerging economy efforts.*

Emerging economies[1] are tremendously important to reaching the 2DS. *Energy Technology Perspectives* (*ETP*) analysis indicates that global demand for energy will increase rapidly in coming decades due to population growth, per-capita increases in gross domestic product (GDP) and continued urbanisation. While emerging economies start from a much lower level of energy consumption compared with OECD countries, all three factors are particularly pronounced in these regions. As a result, OECD non-member economies will account for around 90% of energy demand growth to 2050 across low carbon *ETP* scenarios. The People's Republic of China (hereafter "China") alone, where demand has surged by 100% over the past decade, accounts for more than 26% of projected demand growth to 2050.

A related, internal challenge is that many emerging economies show marked disparities in energy access: while some of the population has begun to adopt energy-intensive lifestyles, many citizens subsist without access to modern energy services. Tackling energy poverty and expanding energy access beyond meeting basic domestic needs is of critical importance to these governments.

Achieving the 2DS will require that all countries make concerted efforts to decouple energy demand from economic growth, and a major transformation and rapid decarbonisation of

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[1] ETP data cited in this chapter focuses on a particular group of emerging economies which have the ability to reduce their CO_2 energy and industry sector emissions by 75% by 2050 relative to the 6DS, namely Brazil, China, India, Russia, South Africa and Association of Southeast Asian Nations (ASEAN) economies. However, some of the approaches and examples discussed throughout the chapter are also likely to be relevant in helping to set a low-carbon transition trajectory for other OECD non-member economies with varying technological capabilities and smaller markets.

energy systems. The unique role of emerging economies at this point in time is that recent technology innovation creates an opportunity for them to choose a different – and more sustainable – path to economic and social development. Ultimately, the path emerging economies follow will have local and global implications: following the same path as most OECD countries would lead to global environmental degradation on a scale that would put economic growth, security and well-being at risk.

Examining the benefits and opportunities emerging economies could derive from adopting a low-carbon technology path, as well as the inherent challenges, is globally relevant and significant for all. National governments will have a critical role in establishing a policy environment that encourages innovation of low-carbon technologies across all sectors, and in securing finance and investment. International collaboration will play an important role in strengthening that environment.

Low-carbon technologies are urgently required to mitigate CO_2 emissions in emerging economies. To date, most of the available technologies have been developed in OECD countries and designed to meet conditions in those contexts; whether they will be well suited for emerging economies is not always straightforward, which raises the question of how emerging economies can best acquire solutions that meet their needs. One of the first things this chapter examines is how emerging economies can gain access to low-carbon technologies – whether using strategies to “adopt, adapt or develop” (Box 7.1).

Energy demand growth is closely linked to increased emissions – a primary motivation for emerging economies to shift to low-carbon technologies. Together, the emerging economies of Brazil, China, India and South Africa have the potential to reduce their CO_2 emissions by 75% by 2050 relative to the baseline (Figure 7.1). China alone accounts for 29% of the total 2DS savings in 2050.

Besides reducing emissions growth, there are other reasons for emerging economies to shift to a low-carbon path. In addition to delivering reduced CO_2 emissions, many low-carbon energy technologies have economic, social and environmental benefits. While quantifying such impacts – and, ideally, calculating an associated economic value – can be highly complex, the results can help leverage some of the wider positive impacts of specific low-carbon technologies and effectively lower the net costs of emissions reduction.

A study financed by the European Union estimates that if external costs for damage to the environment and health (excluding costs associated with climate change) were taken into account, the cost of electricity produced from coal would double, and the cost of electricity produced from natural gas would increase by 30% (ExternE, 2001). The external costs of energy production and use in the United States in 2005 (again, excluding costs associated with climate change) were estimated at USD 120 billion, largely attributable to human health consequences of air pollution from electricity generation and motor vehicle transportation (NAS, 2009). In China, the external cost of pollution – e.g. health costs, and losses in labour and land productivity – amounted to 3.8% of GDP in 2005 (World Bank, 2007). Another assessment suggests that properly accounting for the costs of air pollution could reduce the true incremental cost of climate change to society by half or more (IRENA, 2014).

Recent IEA analysis that identifies and quantifies a range of “multiple benefits” of energy efficiency finds that when their full value is calculated alongside traditional benefits of lower energy demand and emissions reduction (e.g. enhancing system sustainability, supporting strategic objectives for economic and social development, promoting environmental goals, and increasing prosperity), energy efficiency measures can deliver returns as high as USD 4.00 for every USD 1.00 invested (IEA, 2014e).

Box 7.1 Ways to acquire low-carbon technology: Adopt, adapt or develop

Generally, low-carbon technologies flow to and/or among countries through several channels, which can be grouped under three broad categories:

- **Adopt:** technology adoption refers to cases in which a technology is acquired from external sources and then absorbed (i.e. put to use) without any changes to its parameters.
- **Adapt:** technology adaptation refers to cases in which a technology is acquired from external sources and then absorbed by changing certain parameters.
- **Develop:** technology development refers to cases in which the innovation is carried out domestically; the technology may be developed by research institutes or private firms, or through collaboration among multiple partners. The technology parameters reflect local needs.

The acquisition channel depends on the type of technology desired and its stage of maturity, as well as on the characteristics of the countries and firms involved – including their capacity to adopt, adapt or develop. The speed and effectiveness of technology innovation will depend on other issues, such as whether the technology is under patent or in the public domain; whether it is mature and can be easily absorbed or is cutting-edge and requires extensive know-how and tacit skills for implementation; whether it is already commercialised or requires further development (e.g. through RDD&D collaboration); and whether it is, in fact, suited for the local context.

Ultimately, the choice of channel is a commercial decision, reflecting a firm's choice to acquire the technology from an outside source or try to develop the solution itself. Developing the technology has the advantages that it will be tailored to meet local or country needs, and any resulting innovation will be the intellectual property of the developer. However, domestically generated technology typically has a higher cost than "off-the-shelf" solutions acquired from external sources, and requires a high level of local technological capacity.

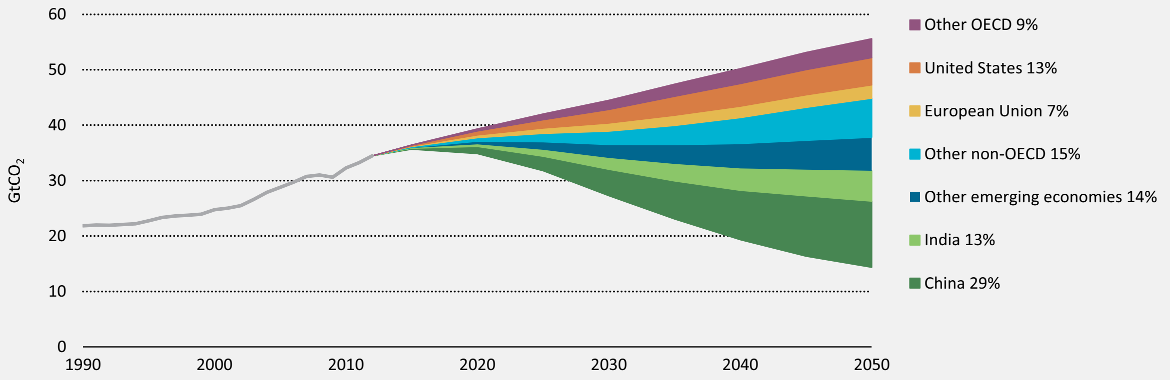
While there might be political and economic reasons to develop a technology indigenously, circumstances may warrant caution against moving too quickly. Lack of technological capacity, shortage of critical components or insufficient skilled labour could undermine efforts by pushing up the cost or slowing the pace of deployment. Nevertheless, external technology acquisition typically requires some degree of adaptation to the recipient country context, adding to the cost and time of technology deployment.

Some forms of technology acquisition combine both domestic and international activities, as in the case of international collaborative research, development and demonstration (RD&D) and modification of foreign technologies to suit the local context.

To accelerate technology innovation and steer it beyond the level markets would achieve on their own, countries need to devise their own acquisition priorities and strategies. Later sections of this chapter explore the specific channels, pathways, market mechanisms and policy instruments that have proven effective for increasing innovation of low-carbon technologies in emerging economies, offering insights and lessons learned.

Indeed, some emerging economies have already stepped up efforts to promote clean energy technologies driven not by climate concerns but by imperatives for development and poverty alleviation, local environmental protection, and energy security (Chandler et al., 2002). Brazil's biofuels programme, for instance, was aggressively supported as a way to reduce energy imports and diversify energy supplies.

Figure 7.1 World energy-related CO_2 emission abatement by region between 6DS and 2DS



Notes: $GtCO_2$ = gigatonnes of CO_2. Figures and data that appear in this report can be downloaded from www.iea.org/etp2015.

Key point *In the 2DS, select emerging economies contribute the majority of energy-related* CO_2 *emissions reduction.*

Emerging economies have the greatest opportunities over the long-term to capture the full benefits of a low-carbon revolution by capitalising on the synergies between development and environmental priorities to advance simultaneously on both fronts (Sathaye et al., 2007). In this sense, fostering low-carbon technology innovation can be applied as a strategy to achieve broader national objectives, such as becoming a leader in a particular field of technology. For instance, China has articulated a clear and coherent plan to become a leader in clean energy innovation, manufacturing and deployment, as outlined in China's Five-Year Plans (discussed in detail in Chapter 8).

This chapter aims to demonstrate the benefits for emerging economies of shifting quickly towards a low-carbon innovation path. The overriding message is that even in contexts of resource or other constraints, stemming from shortfalls in human capacity, education, and high financial and political risks, emerging economies would do well to set off on low-carbon energy pathways in the very near term. The chapter then provides guidance for establishing a systematic process to select priority technologies.

To strengthen their position in low-carbon markets both nationally and internationally, emerging economies will need to pursue a strategic mix of options to acquire technologies, including licensing, trade, foreign direct investment (FDI), joint ventures, and mergers and acquisitions of technology-rich firms. Finally, they will also need to be active in RDD&D on various scales.

This implies setting up the policy framework and conditions needed to create an enabling environment for low-carbon technology innovation. This is achieved by creating demand, strengthening local technological capacity, lowering barriers to trade and FDI, enhancing intellectual property rights (IPR), and securing access to low-carbon finance.

The innovation needs of emerging economies will go beyond technology development and deployment capabilities. To create an environment conducive to sustainable investment decisions, governments will need to adapt financing and regulatory spheres, as well as build capacity related to business models, marketing, installation, and operations and maintenance (O&M).

A section towards the end of the chapter considers the role of some specific technologies in achieving the 2DS across emerging economies. It examines both supply and demand sectors, emphasising the importance of advancing towards low-carbon energy sources while effectively managing the use of conventional technologies during the transition – particularly to avoid "lock-in" of high-carbon technologies. The chapter closes with policy recommendations for emerging economies – and for OECD countries that need to be players in this transition to a more sustainable pathway.

Acknowledging that emerging economies have varying technological capabilities and smaller markets – and thus have different priorities and face different challenges – it is important to stress that national strategies will need to be carefully customised. Yet the content of this chapter outlines some key areas for targeted action. Other OECD non-members transitioning into emerging economies and strengthening industrial and manufacturing sectors may also find some benefit in considering opportunities and challenges they will face in the near future.

Reshaping deployment trends in emerging economies

In the last decade, deployment of most low-carbon technologies has been concentrated in OECD countries. But a fundamental shift is under way: emerging economies have achieved the greatest gains in deployment in the past few years, and are poised to step into the lead. To reach the 2DS, this trend must be both augmented and accelerated: around 2020, OECD non-member economies will need to be on par with OECD countries in terms of annual solar PV or wind deployment, and will have to overtake them shortly after (Figure 7.2).

Technically, emerging economies have an opportunity to establish a development path based on high energy efficiency and predominantly clean fuel sources. They have a distinct advantage in that many are now engaged in long-term energy planning and in rapidly expanding their energy infrastructures. They are less "saddled" than most OECD countries with extensive carbon-intensive infrastructure, markets, regulations, institutions and customs – all of which are major barriers to the uptake of low-carbon technologies. A large portion of the infrastructure and energy systems that will support rising energy demand in emerging and other OECD non-member economies has not yet been built; ergo, significant opportunity exists to shape a more sustainable future through innovation and application of BATs that improve efficiency and reduce and/or eliminate future emissions.

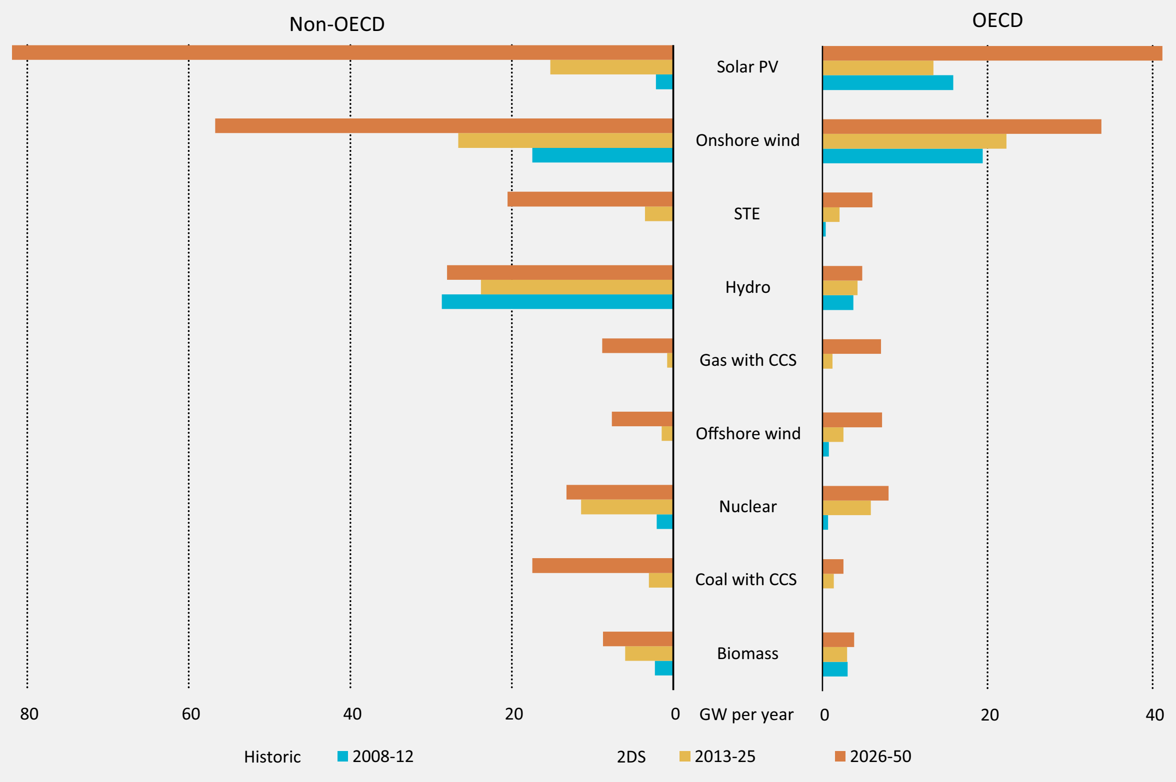
The opportunity to bypass the traditional energy-intensive development pathway followed by OECD countries comes with the overriding challenge: this path is "the road less traveled". Not all emerging economies will be ready to be a front runner in transforming energy systems with low-carbon technologies in both supply and demand sectors early on. The degree of readiness reflects a range of technological and non-technical factors.

To balance these opportunities and realities of the road less traveled, one broad lesson to emerging economies is the need to integrate low-carbon considerations into national planning and related strategies. Steps governments should consider taking include (OECD, 2012; IEA, 2014d):

- Identify the plans that direct national policy, institutions and public expenditures.
- Assess the degree to which each of the above plans aim at low-carbon outcomes.
- Analyse trends and coherence, and identify synergies and gaps.

- Assess low-carbon opportunities, their efficiencies and added value.
- Consult with key stakeholders, business and civil society.
- Identify broader economy-wide enabling policies required to deliver low-carbon benefits (e.g. investing in low-carbon innovation, removing fossil fuel subsidies, building human and technical capacity).
- Develop low-carbon policies and particular instruments for delivery (e.g. green public procurement, clean energy investments and incentives).

Figure 7.2 Power sector technology deployment rates in the 2DS



Note: GW = gigawatt.

Key point *The need to ramp up deployment of low-carbon technologies in emerging economies reflects the challenge of keeping pace with projected energy demand growth in a sustainable manner.*

Setting forth on the road less traveled

The single most important factor for emerging economies with rapidly expanding and evolving energy infrastructure is that uptake of low-carbon technology innovation provides the opportunity to avoid locking in to the carbon-intensive technology and infrastructure that characterises most OECD countries. This implies moving towards renewable energy sources, improving energy efficiency, in some cases including nuclear, and changing the role of fossil fuels.

A particularly important consideration is that the 2DS projects a dramatic increase – with a share exceeding 28% in 2050 – of variable renewable generation, including wind, solar, and ocean energy. OECD non-member economies account for 65% and emerging economies account for 51% of this growth, with new deployment being highest in China and India, consistent with the anticipated large-scale build-up of electricity infrastructure. Emerging economies typically have "dynamic" power systems: that is, they are characterised by high growth rates in electricity demand and/or facing significant capacity investment requirements in the short term. Such systems can be planned and built out taking into account VRE targets, thus avoiding the need for later retrofits (IEA, 2014c).

Increased deployment of VRE creates challenges for maintaining adequacy and security of electricity systems, and requires improved planning and operation. Many emerging economies have long relied on fossil-based natural resources and built existing infrastructure accordingly. They need to carefully manage a new role for these assets, integrating them with expanded VRE inputs. Failure to properly plan for the integration can drive down the value of existing assets, drive up generation costs and complicate further expansion of renewable power.

The dynamic systems of emerging economies may offer better opportunity to balance supply and demand in ways that avoid putting incumbent generators under the level of economic stress that has been seen in trying to integrate VREs in OECD countries (Box 7.2).

Box 7.2 Managing assets to avoid "lock-in" during system transformation

In the much-needed bid to expand energy systems in emerging economies, many countries have recently built fossil fuel-fired power generation facilities. Once such investments are made, it becomes very difficult to avoid using these facilities: payback to investors depends on the plants being operational for 30 to 40 years, and social and political pressures encourage lock-in of incumbent interests, which renders societies dependent on high-carbon pathways. In fact, previous IEA analysis (2013a) shows that continued operation of existing fossil energy infrastructure alone, from power plants to oil wells, would emit 80% of the CO_2 emissions allowable through 2035 under a 2°C goal. This suggests there is limited "room" for new fossil fuel infrastructure.

But that finding has not altered reality: other major fossil fuel expansion projects are already under way or being considered in many countries. Mexico and Brazil are pursuing deepwater oil drilling, while China and India continue to open coal mines and coal-fired power plants.

While failure to transition quickly to low-carbon generation in emerging economies will lock in CO_2 emissions for decades – and make the change in course towards the 2DS more costly – the nature of VREs creates some challenges that must be fully considered. The most important factor is that VREs do not deliver consistent levels of energy, all the time. When their output drops, system operators need to call on other assets that provide "flexibility" (e.g. power plants, grid connections, storage assets or demand-side response options). Such assets are readily available in OECD systems, but already suffering from system transformation in that as VREs contribute larger shares of power generation, they are producing below the level needed to ensure efficient operation and satisfy investment calculations.

As low-carbon systems in emerging economies are unlikely to have the same level or mix of flexibility assets, long-term investment strategies for additional system flexibility are needed at earlier stages of VRE deployment. This raises the importance of applying planning tools that take into account VRE in longer-term system planning.

Investing in the infrastructure to employ cleaner and more efficient energy technologies must be underpinned by supportive regulatory frameworks and business models. Where such effort has not been taken, problems identified have ranged from lack of network connections in Brazil to grid strain from production "hotspots" in India, or failure to provide incentives to enable fossil fuel plants to adjust their output to complement varying wind or solar PV production in China (Global Commission on the Economy and Climate, 2014).

But positive examples also exist. China is developing the largest high-voltage direct current (HVDC) transmission infrastructure worldwide, which provides great opportunity for increased transmission efficiency. At the same time, it is also setting up an HVDC manufacturing base that is displacing imports and could challenge the biggest global players in the market (Pei, 2013).

Reorienting emerging economies for low-carbon technology innovation

The primary role of governments is to create a policy environment that enables the private sector to select the most efficient technological solutions, determining which technologies to play a leading role in RDD&D efforts, which technologies to be strongly positioned to follow international developments quickly, and which technologies to adopt a wait-and-see approach, monitoring international developments and following as needed. This includes setting clear government objectives that will help to set technology priorities – a critical step that requires reliable data, which is often lacking in emerging economies. RDD&D budgets then need to be aligned with objectives and supported by long-term, strategic policies that evolve as conditions change.

Setting technology priorities

Setting technology priorities in emerging economies presents a particular challenge, as both the contexts and technology opportunities are evolving rapidly. Although the same low-carbon technology options are broadly available to both OECD countries and emerging economies, the latter are likely to face additional challenges in wide-scale deployment. This may be especially true of technologies in very early stages of commercialisation, that need very large initial capital investments, or that require substantial outside expertise to operate and maintain over the lifetime.

An IEA review of stated energy RD&D priorities in various countries, which assesses announced technology programmes and strategies against recent spending trends, finds some important deviations. While countries have been favouring certain technologies through allocation of funding, in practice the decisions seem somewhat random; clear priorities are not always based on structured analysis and documented processes (IEA, 2011c).

Many tools are available to help governments inform critical choices, including technology intelligence, forecasting, roadmapping, technology assessment and foresight. Even so, the use of quantitative data or highly developed criteria and formulas should not be expected to provide ready-made answers to priority setting, but rather provide direction and insights to guide choices. Understanding core aspects, rather than the mastery of tools, is the most important element in priority setting. The three most important aspects include the use of criteria, the process and the choice of stakeholders involved.

Establishing various criteria that depend on quantitative data can be used to avoid subjective judgement. Scores can be calculated for each of the criteria being considered, such as reduction of energy imports or CO_2 emissions, expected return, human capacity, and technical and financial feasibility. The social and environmental impacts of supporting specific technologies should also be taken into account. In some cases, the criteria may reflect areas in which a country has a particular competitive or cost advantage. Country-specific contexts and needs will drive the formulation of priorities, and form the basis for prioritising energy technology development.

Priority setting is a continuous process. In fact, how the priority setting is carried out may determine the results of the exercise as much as the set of criteria used. The process is most often based on an explicit or implicit vision of the long-term energy future, and typically includes selecting participants, acquiring data and agreeing on criteria. Applying a consistent framework is critical, particularly when comparing various technologies over a range of time frames and policy scenarios, with respect to their expected benefits and costs.

A systematic process for priority setting also involves engaging and communicating with stakeholders and a wider public. To the extent that procedures for prioritising and selecting are well described and transparent, a structured approach (methodology) to priority setting can generate legitimacy for a process that involves conflicting interests, and ultimately increase acceptance of the outcome (IEA, 2007).

As national policies and strategic goals for energy and technology development evolve, governments need to review priorities and related policies. Stability and long-term horizons are key in obtaining results – but so is the ability to adapt support policies to change.

Data needs in setting technology priorities

To effectively plan and set priorities for technology deployment – and to attract investment – emerging economies need extensive knowledge of their energy resource potential. Lack of reliable and easily accessible resource assessments, including renewable resource data, is a primary obstacle to both public and private sector support to low-carbon technologies. There is a significant need to develop refined estimates of low-carbon resources worldwide, and to capture the information in such a way that it can support effective planning and investment. In some cases, accurate preliminary information needs to be verified by on-the-ground assessment (Box 7.3).

Status of low-carbon innovation in select emerging economies

As energy use and CO_2 emissions increase in emerging economies, there is an urgent need to better understand the size of their RD&D budgets, their energy innovation policies, and the effectiveness of their initiatives. Despite various international initiatives, data concerning spending on low-carbon RD&D in emerging economies are still scarce. The IEA collects data on energy technology RD&D budgets, but only among its 29 member countries. Absence of a centralised, reliable source of data for RD&D spending on clean energy makes it difficult to compare countries' initiatives and to estimate global public spending. As few countries collect data for private RD&D, the challenge is exacerbated.

Box 7.3

India's concentrating solar power (CSP) strategy undermined by insufficiently accurate solar resource data

Deployment of CSP (or solar thermal electricity) in India, under the Jawaharlal Nehru National Solar Mission (JNNSM) initiative, was launched in 2010 with seven projects being awarded under Phase I, accounting for a total capacity of 470 megawatts (MW). At present, the initiative is behind schedule: only one project (50 MW parabolic trough plant in Rajasthan) was commissioned before the March 2014 deadline, while two others have since been commissioned (100 MW Linear Fresnel plant, also in Rajasthan, and a 50 MW parabolic trough plant in Andhra Pradesh). Among the main reasons for this delay, one in particular is critical for prioritising CSP technology: the lack of sufficiently accurate direct normal irradiance (DNI) data.

When bidding for Phase I took place in 2010, all project developers based their bids on solar radiation values from solar radiation maps released by National Renewable Energy Laboratories (NREL) in 2009 and 2010 – the first satellite-based solar maps of India. Later investigation found that the NREL maps estimated solar resource values at 15% to 25% higher than actual on-site resource measurements (Muirhead, 2014). Since DNI has a huge impact on the economics of a CSP project, this inconsistency has put the financial viability of the projects at risk: concerns regarding DNI accuracy have undermined developer confidence to submit CSP bids in India. In 2011, a bid issued by Rajasthan for 100 MW of CSP capacity received no proposals. Another solar resource assessment, released in 2012 by the Rajasthan Renewable Energy Corporation Limited (RRECL), found that DNI was 30% below the NREL estimates, adding further uncertainty (Muirhead, 2014).

The government of India is taking steps to strengthen its CSP policy, which include improving the availability of DNI data through solar radiation measurement stations. The Solar Radiation Resource Assessment, overseen by the Centre for Wind Energy Technology within the Ministry of New and Renewable Energy (C-WET/MNRE), installed 51 stations across India in 2011 that have been collecting data for more than two years. Another 61 stations were installed by the third quarter of 2014. India expects to release new solar radiation maps based on these measurements, along with an update of the RRECL 2012 assessment, with the aim of reducing the data uncertainty.

In July 2014, C-WET/MNRE commissioned a national solar atlas for India to secure more accurate solar radiation data, thereby reducing risk and uncertainty to future developers. The work will be carried out by 3TIER, a wholly owned subsidiary of Vaisala and the leading source for global renewable energy assessment and forecasting information.

Even so, the data available on global RD&D show that the share from emerging economies is increasing. In 2008, the governments of six emerging economies (Brazil, China, India, Mexico, Russia and South Africa) controlled larger amounts of energy RD&D funding than the governments of IEA countries. This calculation includes investments by 100% state-owned enterprises (SOEs) (Kempener, Anadon and Condor, 2010), which accounted for around 90% of the total investments in these emerging economies. By contrast, OECD numbers include only direct government RD&D spending, which is minimal compared with private funding in OECD countries. In contrast to most OECD non-members, where RD&D is predominantly funded by governments, countries such as Brazil, China and India see more private sector engagement, with the main source of innovation being adaptation and improvements on existing technologies (Correa, 2011).

Still, data from the European Patent Office Worldwide Patent Statistical Database (PATSTAT) on patented inventions related to climate (by country) show that inventions remain concentrated in OECD countries; China is the only emerging economy in the top five inventors (Table 7.1). This suggests that to reinforce the platform on which they can engage in low-carbon technology efforts with emerging economies, OECD governments should strengthen their own innovation systems while undertaking RDD&D activities domestically with an eye towards applications and needs of emerging economies. Furthermore, there are significant potential benefits from encouraging international collaboration in climate change mitigation technologies.

Evidence shows that a greater number of patentable inventions are produced by OECD non-member economies when their researchers collaborate with OECD countries (OECD, 2014).

Table 7.1 Top ten inventor countries in climate innovation and selected emerging economies

Rank	Country	Share of world climate patented inventions (2000-11)*
1	United States	22.2%
2	Japan	18.6%
3	Korea	14.0%
4	China	13.7%
5	Germany	12.3%
6	France	3.1%
7	United Kingdom	2.3%
8	Canada	1.7%
9	Russian Federation	1.4%
10	Italy	1.0%
Total top 10	-	90.3%
17	India	< 1%
27	Brazil	< 1%
29	South Africa	< 1%

* International patents refer here to claimed priorities invented in the country as a share of world claimed priorities. Mean of 25 climate technology shares.
Source: OECD (2014), *Measuring Environmental Innovation Using Patent Data: Policy Relevance*, Environment Policy Committee, OECD Publishing, Paris.

Patent statistics are a useful indicator of product and process innovation, and can be used to measure the flows of technologies across countries. Similarly, as international trade and FDI are major channels for technology transmission across countries, the inflow of intermediate goods and FDI can serve as indicators of the volume of imported technologies (Glachant et al., 2013). These data show that emerging economies are integrated in the global exchange of climate-friendly technologies, albeit to varying degrees. China accounts for 7% to 15% of the world import of technologies, depending on the indicator used. Russia and India, by contrast, have much lower volumes of inward transfers (between 1.3 and 2.2% for the former and about 1.5% for the latter, depending on the indicators used), considering the respective size of these economies as measured by their percentage of the world GDP (Table 7.2).

Table 7.2 Low-carbon patent inflows, imports and FDI in selected countries as a share of world total

Country	Patent inward flows*	Import of low-carbon equipment**	FD inward FDI links***	Share of 2009 world GDP
China	15.5%	8.3%	7.1%	11.1%
Mexico	2.2%	1.7%	2.5%	2.2%
Russia	1.3%	1.4%	2.2%	3.3%
South Africa	1.2%	0.4%	0.9%	0.7%
India	..	1.5%	1.6%	4.9%
Brazil	0.7%	0.7%	2.5%	2.9%

Note: ".." indicates data is not available.
* Average percentage of total world low-carbon technology patent applications for technologies invented abroad, covering 23 technology classes, except agriculture and forestry (2007-09).
** Average percentage of total world low-carbon equipment import from 18 products/sectors: hydro, wind, solar PV and thermal, nuclear, energy storage, electric and hybrid vehicles, rail locomotives, cement, insulation, lighting, economisers, super-heaters, soot removers, gas recovers (2007-09).
*** Percentage of total world capital links between a source company owning at least one low-carbon patent and a foreign company in 2011.
Source: Glachant et al. (2013), "Greening global value chains: innovation and the international diffusion of technologies and knowledge," *Policy Research Working Paper Series* 6467, The World Bank, Washington, DC.

South-South technology transfer remains limited: the transfer of climate-related patents among developing countries is less than 1% of global flows, and FDI flows are only 1.9% of all FDI links. On a positive note, South-South trade flows have grown to a significant 10% of the world total (Glachant et al., 2013). The United Nations Commodity Trade Statistics database (UN COMTRADE) shows that between 2005 and 2008, China, India, Brazil and Russia increased both imports and exports of a range of renewable energy products and associated goods, with China and India switching from being importers to becoming net exporters of these technologies (IEA, 2010).

Options for acquiring low-carbon technologies: Adopt, adapt or develop

Technology innovation will play a pivotal role in the transition to a low-carbon economy on the global level. By enhancing the portfolio of options available and reducing the cost competitiveness gap between low-carbon technologies and the fossil fuel incumbents, innovation helps to accelerate the decoupling of economic growth from CO_2 emissions, and offers opportunities to meet climate goals at reasonable cost. However, opportunities are diverse among countries, and it is important to distinguish among different types of innovation, e.g. innovation aiming at developing versus deploying new technology.

As outlined in the chapter introduction, low-carbon technology typically flows to and/or among emerging economies through several channels, which can be grouped under three broad categories: adopt, adapt or develop. Economic literature argues that technology and related knowledge spread through three main channels: licensing, international trade and FDI (Maskus, 2004). Other sources also include joint venture (JV), acquisition of a technology-rich firm, domestic RD&D, or international collaborative RD&D. This section explores some of the channels that support each type of flow, as exemplified by China's approach to technology acquisition and innovation (Box 7.4).

Box 7.4 China's approach to technology acquisition and innovation

Energy has long been a main focus area of China's national science and technology strategies, but the country has historically focused on corporate-driven technology transfer. A review of China's approach in the 1980s and 1990s provides evidence that the main avenue to access cutting-edge technology was the attraction of inbound FDI into JVs with local partners (IEA, 2013g).

When China opened its coast to oil exploration in the 1980s, for instance, it fostered JVs between China National Offshore Oil Corporation (CNOOC) and international oil companies to acquire offshore capabilities (Warhurst, 1994). Similarly, the 1996 "Riding the Wind Programme" encouraged JVs between Chinese firms and global wind technology leaders. Toyota's JV with China's leading car manufacturer, Sichuan FAW, led to the Prius hybrid car being produced in China (IEA, 2010).

However, the "trade market access for technology" approach in some cases had limited success, since foreign investors largely preferred to install fully owned subsidiaries due to IPR and operations challenges (Klagge et al., 2012).

As a result, direct government funding for domestic RDD&D has come to play a significant role in Chinese technology development, with a significant increase in total RDD&D spending. In the longer term, however, China aims for enterprises and the business sector to become the driving force of the innovation process (15-Year Plan for Science and Technology 2006-20) (Schwaag et al., 2007). In this context, the acquisition of technology by outbound FDI will have to make a significant contribution. A more detailed discussion of China's innovation system is covered in Chapter 8.

Technology adoption

Tapping into knowledge and foreign innovation is often the most efficient means of acquiring low-carbon technologies. The adopting country benefits from existing competition and co-operation within the international market (OECD, 2012), with greater cost-effectiveness than developing those technologies domestically. Most low-carbon technology diffusion is pursued within the private sector, with adoption by firms and markets playing a significant role. Focusing on technology adoption is particularly fitting in countries with lower technological capabilities and smaller domestic markets.

Licensing

Some emerging economies use licensing as a primary strategy for technology acquisition. This occurs when a company and/or research organisation grants a patent licence to another firm. The agreement allows the firm which acquired the license to access the know-how behind the technology and to use it under the licence terms. The bulk of the payment is generally in the form of a royalty. For example, Goldwind (one of China's largest wind technology manufacturers) initially acquired access to wind technology by purchasing licences from German wind turbine maker Vensys (IEA, 2010).

A company's willingness to license the technology is often based on factors such as market structure and the level of intellectual property protection in the recipient country, as well as the capability of the licensee to assimilate and imitate the IP. Fear of the technology being copied by recipient firms is a serious consideration, as is evident in the reluctance to license clean coal combustion technologies to China (Vallentin and Liu, 2005) among other clean energy and ICT technologies. Clear rules concerning ownership of patents, and the boundary and scope of national protection and enforcement mechanisms, are critical in determining the frameworks for establishing legal agreements that enable access while protecting innovation.

Trade

Trade, involving the purchase of production equipment or machinery with embedded technology, is probably one the quickest and lowest-risk forms of technology acquisition – even though installation of the new equipment may require some support in the form of training and maintenance. Openness to trade and investment can help to ensure access to the BATs whereas tariff and non-tariff barriers to trade can hinder technology diffusion, for instance by increasing the costs of deploying low-carbon technologies.

For example, tariffs on ethanol and some biodiesel feedstocks (including Brazilian ethanol), combined with subsidies to domestic biofuels producers from OECD countries, are preventing investment where the technology is most cost-effective. Similarly, EU tariffs of as much as 57% on compact fluorescent lamps imported from China have led to a significant decline in Chinese exports to European markets (Brewer, 2009).

Research shows evidence that eliminating tariff and non-tariff barriers in the top 18 greenhouse gas-emitting developing countries would increase imports by 63% for energy efficient lighting, 23% for wind power generation, 14% for solar power generation and 4.6% for clean coal technology (World Bank, 2007).

Liberalising trade and removing trade barriers can open export markets and make it easier for producers to access international value chains of low-carbon products. Since some emerging economies export as many low-carbon goods as high-income countries, significant potential exists for emerging economies to grow their economies based on the export of low-carbon goods and services.

Foreign direct investment

Multinational firms are important sources of technology activities, and often provide knowledge and skills to local firms in recipient countries. They can diffuse low-carbon technologies to emerging economies through FDI in wholly owned subsidiaries or other foreign affiliates. In fact, many multinational firms have been expanding their RDD&D activities to emerging economies, which allows these countries to participate in global RDD&D networks.

At the same time, some emerging economies have implemented proactive policies to leverage FDI as a means to acquire desired technologies. For instance, Brazil uses its development bank, BNDES, to subsidise foreign firms that produce domestically, which encourages countries to transfer their technology into Brazil (Levi et al., 2010).

Multinational firms based in emerging economies can create different opportunities. One firm based in India is a notable example: Tata, a conglomerate with interests in energy, transportation and other low-carbon relevant industries, has wholly owned subsidiaries, JVs and other forms of agreements for RDD&D and manufacturing in more than two dozen countries (Brewer, 2009).

Since multinational firms sometimes engage in FDI as an alternative to circumvent trade barriers, it is also important to consider how barriers to FDI create significant obstacles to diffusion of low-carbon technologies.

Joint ventures

A JV agreement typically takes the form of a partnership between two firms, one with a technology and the other with market access, creating a relationship that is much closer than in licensing. This approach has the advantage of greater possibility for mutual learning – about the technology and/or the market (Aswathappa, 2010).

As discussed in Box 7.5, China has encouraged JVs (as opposed to FDI) to maximise technology access by local firms. This strategy, however, is likely to work only for countries with sufficient market power, and carries the risk of transferring substandard technologies.

Mergers and acquisitions

Strategic purchase of companies – often those based in OECD countries – which have the know-how that an acquiring firm desires is another form of external technology acquisition. Although technology acquisition may not be the primary driver in many of these purchases, it does facilitate increased technology diffusion.

For example, Suzlon Energy Limited, an Indian wind turbine manufacturer founded in 1995, was initially developed so that founder Tulsi Tanti could provide power to operations of his family textile business. Within a decade, the company became one of the world's largest wind turbine manufacturers, with operations in over 15 countries. A key component of Suzlon's rise has been the acquisition of European wind energy technology companies, including AE-Rotor Techniek of the Netherlands in 2000, Hansen International of Belgium in 2006, and REPower of Germany in 2007 (IEA, 2010).

Technology adaptation

Currently, most low-carbon technologies are developed in OECD countries without consideration for the natural resource or labour endowments of OECD non-member economies and with little regard for the basic needs of people living in these regions (Aswathappa, 2010).

Adapting an acquired technology to emerging economy contexts may be necessary for several reasons, such as meeting geographical and/or market-specific needs, making the technology compatible with existing plant, machinery or energy resource characteristics, or to comply with legal requirements. Modifying and adapting technologies developed by OECD countries to the different needs and conditions of OECD non-member economies requires significant effort. At minimum, domestic capacity is necessary to understand the technologies and to adapt them into solutions for a specific application. Such adaptation can create an important market opportunity. Technologies adapted to the conditions of one emerging economy may be well suited to the needs and conditions of other OECD non-member economies.

Clauses restricting the conditions of technology transfer can compromise the ability of recipient countries to optimise the technologies for local contexts, for example by outright prohibiting adaptation of the imported technology, preventing its use as basis for local RD&D, or stipulating that outcomes of domestic technological RD&D based on the imported technology must be transferred to the original owner or supplier (Aswathappa, 2010). Such clauses should be strongly discouraged by all parties, since they act as a disincentive to domestic innovation.

Technology development

Evidence shows that countries that innovate domestically are more likely to benefit from innovations acquired from external sources (Levi et al., 2010) – an important consideration for emerging economies.

This strategy may produce a high payoff as emerging economies, in turn, export their own clean energy innovations. Emerging economies can try to gain a competitive advantage by being "first actors" and thereby realise the benefits related to competition in widening international markets. Recent innovations from emerging economies (as opposed to those from OECD countries) are proving to be more suited to the needs and conditions of other OECD non-members in similar development stages (OECD, 2012).

This strategy can also help expand South-South innovation and collaboration, and facilitate pooling of resources to achieve common objectives, building on existing experiences. One example is the knowledge-sharing platform, initiated in 2009 by China and intermediated by the Asian Development Bank (ADB). The platform facilitates dialogue to strengthen partnerships and networks on issues and challenges confronting China and other developing countries in Asia and the Pacific (ADB, 2012).

As China, India and Brazil, among others, have already demonstrated, emerging economies can participate in the low-carbon technology revolution as innovators rather than simply technology takers – either through domestic RD&D initiatives or by taking part in international collaborations.

Domestic RD&D

Several factors may warrant pushing emerging economies to play a lead role in RD&D for a particular technology. Such efforts may, for instance, be closely tied to domestic markets, as in the case of Brazil's biofuels industry designed mostly to serve domestic needs, however with considerable trade impacts in recent years. Similarly, Chinese efforts to develop wind technology were also driven largely by initiatives to promote domestic deployment (Levi et al., 2010).

Moreover, OECD non-members often face some technological challenges that are unique and shaped by local or regional circumstances; solutions may require indigenous development through domestic RD&D. Deploying integrated gasification combined cycle (IGCC) for power generation in India is a case in point: the Indian government has invested in domestically designed IGCC technology that is suited for use with the country's low-quality coal (Box 7.5).

Box 7.5

India's effort to develop IGCC domestically

While there was extensive global development of IGCC technology in the 1980s and 1990s, higher capital and operating costs led to a general decline in interest in favour of pulverised coal technology. However, IGCC units exhibit some advantages over conventional pulverised fuel for power generation. They can match the efficiency of large state-of-the-art pulverised fuel units (> 400 MW) and can be more efficient at smaller sizes. They inherently emit less air pollutants and have lower water consumption. Consequently, as a result of the potential benefits, developments in India continued. For high ash Indian coals that are typically characterised by higher melting points, studies have shown the air-blown fluidised bed gasification system to be the most suitable form in terms of cost, process efficiency and environmental impact.

Indian developments have mainly been led by Bharat Heavy Electricals Ltd., a state-owned enterprise, which has focused on domestic efforts to demonstrate the technology rather than trying to leverage foreign IGCC technology.

More recently, in the drive to develop low-carbon technology, foreign interest in IGCC has reawakened. IGCC with carbon capture offers the potential for lower capital costs and lower operating costs than pulverised fuel technology with carbon capture. Of particular note is the 582 MW Kemper County IGCC plant with carbon capture and storage, designed to use low-quality Mississippi lignite, that is due to be commissioned in May 2015 (GCCSI, 2014).

Accordingly, now that domestic effort is delivering results, India may do well to engage in collaborative, cross-industry, international initiatives to fully benefit from IGCC innovation taking place elsewhere. This would allow India's experts to share information on advanced coal technologies, perhaps offering a means to reduce the risks and future costs associated with IGCC.

Investing in RD&D for a specific technology need not be tied to domestic deployment: the aim of becoming an international leader is equally valid. The Chinese government has designated clean energy as a "strategic new industry", and the Ministry of Commerce has promoted clean energy technology exports. The Chinese solar PV industry, for example, has been built almost entirely on the back of foreign demand. Although China has focused its market penetration efforts primarily on OECD non-member economies, it has managed to penetrate solar technology markets in OECD countries as well (Levi et al., 2010).

In the case that markets in OECD countries provide few incentives for innovation of a given technology, local innovation can influence RD&D areas to broaden application in emerging and developing economies.

International collaborative RD&D

International collaboration on low-carbon RD&D allows countries and firms to share risks and costs, and enables parties to learn from each other. Yet it must be acknowledged that RD&D partners are often market competitors, so the area most conducive to technology acquisition through this mechanism is applied research that would benefit the whole industry/sector but is too risky or expensive to be handled by a single country, company or research institute. To benefit from participating in collaborative efforts, a given country must have the internal RD&D capability to translate the research results into technology that domestic firms can use.

International co-operation agreements on low-carbon RD&D involving emerging economies have intensified in recent years. An interesting example of company-driven collaborative RD&D is wind turbine manufacturer Suzlon, which adopted a strategy of expanding its RD&D facilities in several countries in Europe, and engaging in collaborative RD&D (IEA, 2010).

The IEA has a long history of facilitating international RD&D co-operation through its Implementing Agreements, which involve co-ordinated research, joint projects, information exchange, modelling, databases and capacity building. The work of the IEA Experts' Group on R&D Priority Setting and Evaluation (EGRD) suggests that successful international energy technology RD&D collaborations share the following characteristics (IEA, 2011c):

- objectives closely aligned with national priorities
- clearly defined scope and timeline/milestones
- based on common interest and mutually advantageous
- strong commitments to successful co-operation and collaboration
- attention to overcoming barriers such as IPR and inadequate legal rules and procedures
- clearly defined roles and responsibilities
- clear measures of success and criteria for evaluation
- broad stakeholder participation.

Manufacturing capacity as an anchor of innovation

Globalisation has prompted a large shift of manufacturing capacity from OECD countries to emerging economies, notably in East Asia, giving them the opportunity to sidestep conventional technologies and introduce more sustainable models of production to gain competitive advantage. This can be done, for instance, by implementing strategies that take into account the manufacturing spread and sector differences, building or retrofitting factories to be more resource-efficient, creating economic zones, and developing effective regulation, incentives and standards in low-carbon manufacturing (OECD, 2012).

In particular, Brazil, China and India have demonstrated the capacity to reorient their manufacturing base and organise their labour markets, leveraging human capacity, investment and technology towards a stronger, more dynamic and competitive low-carbon economy. These countries already play lead roles in developing, manufacturing, deploying and exporting (including to OECD countries) clean energy technologies such as solar panels, wind turbines and biofuel technologies. All three are starting to reap benefits from decades of investments in education, research infrastructure and manufacturing capacity (UNCSD, 2011). Since 2008, for example, China has been the largest producer of low-carbon technology in financial terms, accounting for 1.4% of its GDP (ADB, 2012).

Manufacturing capacity for low-carbon technology is critically important for sustaining economic growth. A skilled labour force can attract new investment and catalyse new jobs, while the ability to compete in manufacturing low-carbon technologies invented and innovated elsewhere can drive domestic innovation for technology development, particularly for capital-intensive technologies. Establishing domestic manufacturing plants also allows firms to better understand the needs of local markets, and can lead to more market-relevant innovations (Kawamura, 2014). Proximity to the manufacturing process can create innovation spillover across firms and industries, leading to new ideas and capabilities that support the next generation of products and processes.

In these ways, a vibrant manufacturing sector is inextricably linked to a nation's capacity to innovate (PCAST, 2012); in fact, the success of innovation often depends on the success of domestic manufacturing. Co-location of RD&D and manufacturing is especially important when technologies are in the formative stage; the value added from the two will benefit the innovating firm and is particularly important to leading-edge manufacturers (Tassey, 2007).

In the initial wave of low-carbon technology innovation, some countries have set their sights – and assessed their value – on innovation alone. They subsequently saw the value created by innovation follow manufacturing overseas, and experienced a loss of RD&D competencies. Now there is greater recognition that manufacturing is important to maintain engineering capacity, which is key to conduct the RD&D needed to adapt technologies for local use and to generate socially and economically relevant new technologies. In fact, some argue that losing manufacturing exposure makes it harder to come up with innovative ideas (Fuchs, 2006). Some developing countries show (at present) limited likelihood of participating in manufacturing to a large scale, but are expected to have major clean energy deployment. Other, non-manufacturing activities will allow them to capture the benefits of low-carbon innovation. For example, service-driven solutions are often less technically sophisticated and require less up-front capital investment to develop and operate. In addition, services that are inherently local, such as engineering consultancy and planning, will be in high demand.

Five building blocks for increasing low-carbon innovation

Low-carbon technology development has been occurring very rapidly in recent years, with corresponding declines in cost. At the same time, sector players have acquired extensive knowledge about establishing effective support schemes, especially in OECD countries. To bring emerging economies into the market, greater interaction with more experienced countries could help to deploy best practices, share knowledge and demonstrate how to deal with anticipated challenges. It is important that emerging economies can learn from experience while also tailoring policy support measures to their local contexts. Scaling up low-carbon technology innovation requires both technological capabilities and strong policies. Evidence suggests that the details of policy design and implementation, rather than the choice of actual policy type, are of first-order importance, especially in the case of renewable energy policy (IEA, 2011a).

For example, when opting for a feed-in tariff (FIT) scheme (the most common policy mechanism worldwide to spur renewable energy), policy makers from emerging economies face myriad programme designs and parameter choices (e.g. selection criteria of eligible technologies, capacity caps and price schedules). Experience shows that fine-tuning such policies through thoughtful design is paramount to success, ergo, emerging economy policy makers could benefit from lessons learned within OECD contexts. In 2004, Brazil successfully transitioned from a FIT scheme to a sophisticated auction system to support deployment of renewable energy. Recent analysis of 20-year contracts between wind farms and a government-owned utility (under the Incentive Programme to Alternative Sources, PROINFA), suggests that contract design issues coupled with costly monitoring of wind data led to widespread misreporting of capacity factors. This reduced the programme's cost-effectiveness and contributed to the perceived failure of the Brazilian FIT in deploying onshore wind (Assunção, Chiavari and Szerman, 2014). At the same time, many emerging and developing countries have gained valuable experience in renewable energy auctions that could be applied to OECD countries. These topics related to wind and solar PV are discussed in more detail in Chapter 4.

Emerging economy governments must play a central role in creating an enabling environment – through favourable policy and other conditions – that supports the scaling up of innovation and deployment of low-carbon technologies. Such an environment should be founded on the following building blocks:

- creating demand for low-carbon technologies
- enhancing local technological capacity
- lowering barriers to trade and FDI
- strengthening intellectual property rights
- securing access to low-carbon finance.

In fact, these building blocks are vital across all countries, although the relative importance of each may vary from country to country and among regions, and emerging economies may be lagging somewhat behind OECD countries. Thus, it warrants exploring each building block in relation to the context of emerging economies.

Creating demand

Public policies that create demand and provide incentives can substantially accelerate innovation in the area of low-carbon technologies while also imposing constraints on conventional technologies, as demonstrated in an extensive literature review (Glachant et al., 2013). The policy instruments available include a variety of support measures (e.g. economic instruments such as carbon pricing and energy taxes), regulatory measures (such as standards and mandates), and direct public support investment for RDD&D.

Market-based pricing mechanisms are inherently cost-effective as they encourage early action for lowest-cost abatement, and provide incentives for efficient investment decisions. Some emerging economies have already embraced this strategy. India is launching tradable programmes in renewable energy and energy efficiency certificates to meet its national goals in these areas. China is implementing domestic emissions trading programmes through seven pilots.

IEA analysis has found market-driven approaches to be beneficial, but notes the additional value of supplementing carbon pricing with cost-effective energy efficiency and technology policies (i.e. RD&D support and deployment policies) to improve the short- and long-term cost-effectiveness of emissions reduction (IEA, 2012). The success of the policy approach will ultimately depend on the success of carefully designing the package of policies as a whole.

An important lesson from diverse initiatives is adapting policy as innovation and deployment advance. The Brazilian experience with biofuels began with strong government intervention to stimulate a highly innovative period but is now marked by a more conservative attitude towards subsidies. This case makes it clear that subsidies may be needed for decades to promote new technologies, but the ultimate gains can be huge (Box 7.6).

Enhancing local technological capacity

Local technological capability is essential to absorb imported technologies: the recipient environments in which a technology will operate often have unique characteristics and will require some degree of local adaptation. Lack of local technological capability may reduce productivity and international competitiveness, or even prevent the technology from working at all (Aswathappa, 2010).

The capacity to absorb foreign technologies can facilitate its acquisition through channels such as FDI and international trade, and thus wider technology deployment. Countries with strong absorptive capacity derive almost all of their productivity growth from R&D carried abroad (Eaton and Kortum, 1996). This is particularly relevant to emerging economies, as lack of human capacity to undertake technology absorption is a much greater barrier to technology adoption in developing countries than in developed countries (Worrell et al., 2000).

A country's ability to absorb an imported technology can influence not only deployment but also the capacity to innovate. Deploying a technology developed abroad often requires the same skills and knowledge required for innovating. This is the reason adopting these technologies drives domestic innovation for technology development, particularly for capital-intensive technologies and vice versa. Both strategies improve local technological capabilities, as demonstrated by China, which is both the top inventor and the top technology importer of low-carbon technologies among emerging economies (Glachant et al., 2013).

Building technological capacity can be achieved through various means, including education, international co-operative RD&D, public-private partnerships, knowledge diffusion and workforce training. A multi-pronged approach can build the foundation for the different technological competences required at different stages of technology development (Figure 7.3) – or indeed for the diverse capacity needs of different technologies, since highly centralised infrastructure-driven solutions may have very different requirements than more distributed, service-oriented technologies.

In India, recent initiatives to establish dedicated university and training courses for new energy technologies, and to provide training for energy managers and energy technicians, will go a long way to supporting transformation of the energy system and preparing human resources for the challenges ahead (IEA, 2013c).

Box 7.6 Direct government action in Brazil's biofuels programme

Brazil's National Alcohol Programme (Proalcool), set up as a response to the 1973 oil crisis, sought to transform fuel supply for transportation. It was based on state intervention through policies on both the supply and demand sides, and the allocation of large government subsidies distributed to ethanol producers, consumers and auto makers.

- **Supply-side policies:** Agriculture and industrial financing; guaranteed production acquisition; fixed subsidised prices.
- **Demand-side policies:** Mandatory blends for ethanol in gasoline; subsidised and regulated prices for ethanol; promotion of ethanol vehicle adoption in public fleets; subsidies for the purchase of vehicles running on pure ethanol

Thanks to this policy support, the Brazilian biofuels industry grew rapidly until the late 1980s, when falling oil prices, rising sugar prices and a cutback of subsidies led to a decline in ethanol production. In 1997, the Brazilian fuel market was gradually liberalised, extinguishing all price controls.

The government played an important role in supporting the market in its nascent phase and during its crisis in the 1990s. Public RD&D and partnering with automobile producers was key to adapting the internal combustion engine to ethanol, enabling the launch of pure ethanol-run vehicles. Work carried out at the Technical Centre of Aeronautics (CTA), an agency from the Ministry of Defence, was particularly instrumental. In parallel, investments in sugar cane agronomic research, mostly done by the public sector, were also pivotal for lowering production costs and allowing ethanol producers to survive without government subsidies.

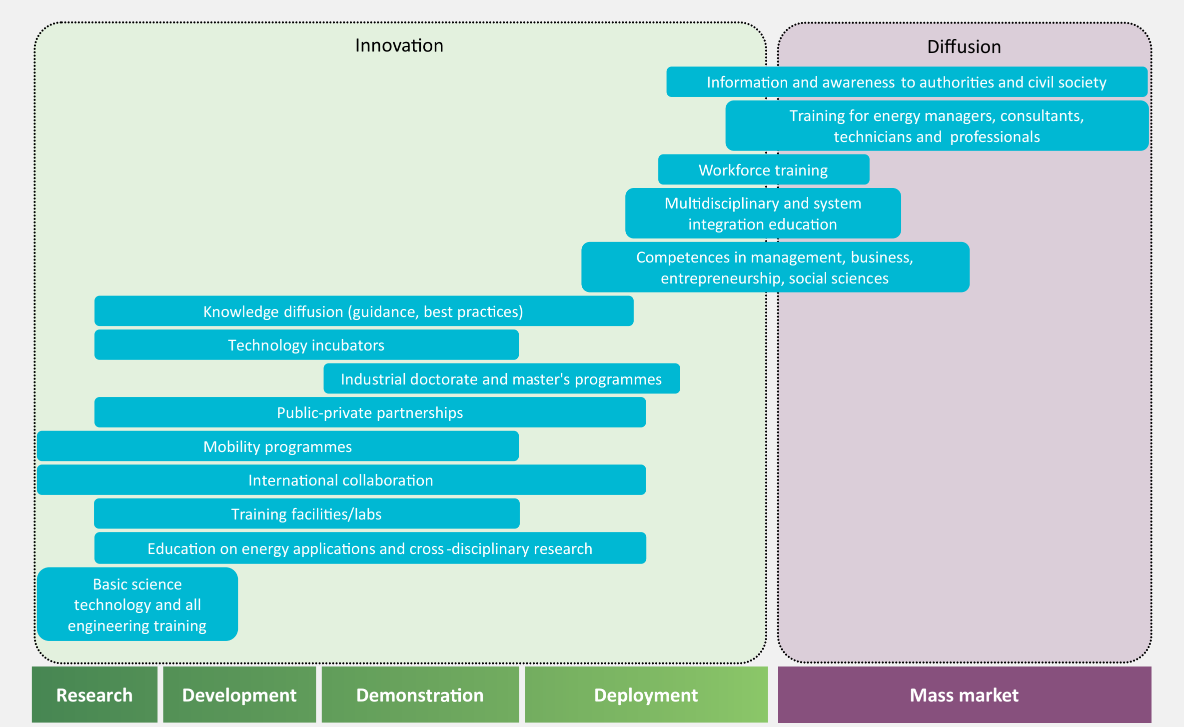
In 2003, the introduction of flex-fuel vehicles (FFVs), capable of running on any given blend of ethanol and petrol, gave a new boost to the ethanol sector. The FFV engine is based on the ethanol engine, modified with the necessary introduction of the electronic injection (Kaltner et al., 2005). The government "pushing" of the automobile industry was pivotal to the technological breakthrough of FFVs.

Table 7.3 Estimated benefits of Brazil's biofuels programme

Reduction in cane ethanol production costs	Averaged about 3.5% per year from 1976 to 1994, making cane ethanol roughly competitive with oil, especially since 2005 (de Carvalho, 1996).
Expansion in sugar and ethanol production	From 1975 to 1983, Brazilian production installed capacity grew from 904 million litres to 11.1 billion litres per harvest (Moraes et al., 2006).
Increase in ethanol productivity	An estimated 51.2% productivity increase between 1980, from 4 200 litres of ethanol produced per cane hectare (l/ha) to 6 350 l/ha in 2003 (Moraes et al., 2006).
Reduction in air pollution levels	Estimated at about 20% (Bajay et al., 1996).
Oil savings	Estimates from different studies vary but all confirm net savings – with some reporting savings of more than USD 50 billion in petroleum imports over 20 years of Proalcool (Goldenberg, 2007).

Sources: Bajay et al. (1996), "Restructuração do Proalcool", *Proc. Congresso Brasileiro de Energia UFRJ*, Vol. 2, Rio de Janeiro, Brasil, pp. 1176–1187; de Carvalho (1996), "A Visao do Setor Sucroalcooleiro", *Perspectivas do Alcool Combustivel no Brasil*, Fernandes, E.S.L. and Coelho, S.T. (eds.), USP Instituto de Eletrotecnica e Energia, pp. 28-48, São Paulo; Goldemberg, J. (2007), "Ethanol for a Sustainable Energy Future", *Science*, Vol. 315, pp. 808–810; IEA (2011c), *Good Practice Policy Framework for Energy Research, Development and Demonstration (RD&D)*, IEA Information Paper, OECD/IEA, Paris; Kaltner, et al. (2005), *Liquid Biofuels for Transportation in Brazil. Potential and Implications for Sustainable Agriculture and Energy in the 21st Century*, Fundação Brasileira para o Desenvolvimento Sustentável, FBDS, study commissioned by the German Technical Cooperation (GTZ), www.bdbe.de/downloads/PDF/fachinformationen/biofuels-for-transportation-in-brazil.pdf; Moraes et al. (2006), *Brazil Alcohol National Programme*, Relatório de pesquisa, Piracicaba, Brazil.

Figure 7.3 Absorptive technological capabilities to increase innovation



Key point *Low-carbon technologies pass through several stages on the route to mass deployment, with different capabilities needed at each stage.*

Successfully accelerating deployment of a foreign technology often requires skills beyond technological capacity, including skills in areas such as financing, business models, marketing, installation, and O&M. These capabilities are essential to reduce the overall cost and risk of innovation. In the same vein, providing support to firms, particularly for SMEs that have a vital role in the innovation process, is critical. Governments, development agencies, and other public and private actors can participate in several key areas, notably entrepreneurship and business acceleration (i.e. assisting entrepreneurs in turning ideas into viable businesses or in scaling up existing businesses).

Traditionally, such initiatives have provided direct training and capacity building to business managers and entrepreneurs, ranging from general financial and managerial skills to targeted support for technical aspects of the business. More recent programmes seek to develop collaborations and networks that help low-carbon technology SMEs share knowledge and experience (World Bank, 2014). Through its infoDev Climate Technology Program, the World Bank has set up Climate Innovation Centers to provide in-country investment and advisory services to low-carbon technology SMEs (Box 7.7).

Lowering barriers to trade and FDI

Technology spread to emerging economies through the market channels of international trade, FDI and licensing has increased substantially in recent decades. Still, policies to further lower and/or eliminate tariff and non-tariff barriers to trade and FDI could increase the traded volume of clean energy technologies by an average of 14% in 18 developing countries with high levels of CO_2 emissions (World Bank, 2009).

Box 7.7 infoDev Climate Innovation Centers

Targeted business incubation and acceleration initiatives are one way to improve local climate technology innovation capacities while also helping encourage more FDI into developing markets.

infoDev's Climate Technology Program (CTP) supports entrepreneurs and SMEs that are developing innovative products and new business models in the climate technology sector. Its flagship initiative is to establish country-level Climate Innovation Centers (CICs), designed as locally owned and operated institutions that provide a suite of venture advisory services and early stage financing opportunities to local climate innovators and companies.

At the national level, CICs provide an important source of early investment in parallel with business advisory and training services, market development services, access to product testing facilities, and government engagement on policy. The CIC acts as a national focal point, co-ordinating efforts to promote development of locally relevant climate sectors. On the international level, the CICs create a platform for business-to-business linkages, trade and investment in local climate sectors.

The CTP views the CICs also as an information-based initiative; the CTP collates information and insights from this network to build, share and apply innovation knowledge worldwide. The CTP has provided policy makers with actionable insights on entrepreneurship and innovation policy, green job creation, sustainable economic growth, and the development of competitive climate technology sectors in low- and middle-income economies.

This growing experience with CICs is beginning to provide lessons about the effectiveness of targeted support to clean technology SMEs across a wide range of developing country contexts. Results are measured in terms of both economic impacts (e.g. growth and job creation of the supported SMEs), and environmental and social impacts (e.g. CO_2 mitigated, increased access to energy or to cleaner water). CICs are now operating in Kenya, the Caribbean and Ethiopia, with additional centres in advanced stages of development in Ghana, India, Morocco, South Africa and Viet Nam.

Source: World Bank (2014), *Building Competitive Green Industries: The Climate and Clean Technology Opportunity for Developing Countries*, World Bank, Washington, DC.

Non-tariff barriers such as local content requirements, which mandate giving preference to local contractors and locally manufactured materials and equipment, are widespread despite being prohibited under the Agreement on Trade-Related Investment Measures (TRIMs) of the World Trade Organization (WTO). Brazil, India and China, among others, are strategically applying local content requirements and technology standards to create export opportunities for their national industries, or to ensure that FDI aligns with broader economic development and technology policy goals. South Africa's Renewable Energy Independent Power Producer Procurement Programme also added local content requirements to bidding criteria to encourage development of local renewable energy equipment manufacturing (OECD, 2013).

Local content requirements can actually delay technology adoption, as seen in China where they led to a domestic shortage of important components and slowed initial adoption of supercritical coal, wind, and EV technologies. A similar challenge has arisen in India's solar strategy (Box 7.8).

While the measures described above can be considered justifiable reasons for local content requirements, the risk is that such policy can create obstacles to bilateral technology flows, lowering incentives for foreign companies to invest locally and reduce imports of equipment or goods. They may also impede foreign companies' access to finance by development banks.

Box 7.8

Local content requirements affecting India's solar energy strategy

Two main technologies underpin the operation of solar panels: crystalline silicon (c-Si) and thin film (TF). To support India's small base of c-Si manufacturers, Phase I of JNNSM (2010-13) included a domestic content requirement (DCR) for cells and modules for c-Si, and a 30% requirement for solar thermal projects. As the TF manufacturing base was even smaller, DCR was not implemented.

Globally, c-Si prices have fallen dramatically and TF has been steadily losing market share – from 30% to only 11% by the end of 2011. In India, on the contrary, the TF share in overall PV installations over Phase I of JNNSM was close to 70%.

This unintended outcome is a result of two factors. First, domestic c-Si manufacturers struggled to compete in a volatile and rapidly declining price environment, led by Chinese suppliers. Second, established TF suppliers from the United States were ready to supply competitively priced modules via low-cost, long-tenor debt from the Export-Import Bank of the United States, the government export credit agency. Faced with an economically attractive option, and supply from more established and proven vendors, developers opted widely for TF.

As a result, DCR did not – as intended – support expansion and development of the Indian manufacturing industry (PV manufacturing actually contracted in size during this period) or make it more competitive in the global market.

Although TF has steadily lost global market share to c-Si, both have relative pros and cons. It is currently almost impossible to predict which technology will perform better in the Indian environment in the long run. This uncertainty, combined with the conflict between global preference for c-Si and India's favour towards TF, might create further challenges for India's rapidly growing solar sector. This unintended outcome also created opposition for extending DCR in Phase II of JNNSM. To make India a leader in solar manufacturing, the government will need to critically evaluate current domestic strengths in relation to the international market situation and competitiveness, and the availability of domestic funds.

Source: World Bank (2013), *Paving the Way to a Transformational Future: Lessons from the Jawaharlal Nehru National Solar Mission Phase I*, ESMAP Paper, World Bank, Washington, DC.

Strengthening intellectual property rights

Issues associated with IPR often arise in discussion of barriers to technology diffusion – usually with no clear-cut resolution in sight. Patents, for example, aim to secure an inventor's ability to appropriate the returns of the invention, thereby providing incentive to invent and to bring inventions into the public domain. But if innovators attempt to prevent competitors from attaining patenting rights to their inventions, patents may actually impede valuable collaboration and information-sharing in the early stages of innovation.

IPR barriers can, in most cases, be overcome by paying a relatively small royalty fee. Yet developing countries perceive the role of IPRs in technology diffusion as a major barrier (Ockwell et al., 2010).

In response, various parties have called for more flexible approaches to protect the public good, such as joint ownership, the creation of patent pools and licensing backed by public support. One practical policy solution for streamlining IPR includes adopting arrangements to fast-track patent approvals for low-carbon technologies, as implemented by a few OECD countries. Separately, some governments are providing financial and capacity-building support to intellectual property applicants and technology developers. Licence-of-right systems provide an incentive to patent holders to make patent licences available to anyone requesting such a licence, with adequate remuneration agreed upon between the patentee and the party seeking a nonexclusive licence, or, in the absence of such an agreement, established by the patent office or a court. The incentive is usually in the form of a reduced patenting fee.

Review of several empirical studies suggests that strict IPR enforcement has an average positive effect on the volume of foreign technology transfers to developing countries, particularly when the recipient country is technologically advanced and open to international trade (Glachant et al., 2013). Other studies confirm these findings in the case of climate-friendly technologies, and show that patenting has not been a barrier for the transfer of solar PV, wind power and biofuel technologies in emerging economies (Dechezleprêtre et al., 2013; Barton, 2007; Maskus, 2010). Since they provide a safeguard against imitation, strong IPR rules are found to encourage the use of knowledge-intensive channels of technology transfer (such as FDI and licensing) instead of favouring the export of equipment and goods (Smith, 2001).

Lack of stringent IPR rules, by contrast, could delay bilateral technology co-operation, as it happened between China and Brazil, as some components supplied by China have recently been subject to scrutiny for potential IPR infringements (IEA, 2013g).

Securing access to low-carbon finance

Meeting the 2DS goals to develop and deploy low-carbon technologies to sufficient levels (both nationally and globally) within a specific time frame implies successfully shifting investments from high- to low-carbon technologies. Overall, the latest *ETP* analysis indicates that additional investment needed to decarbonise the energy system in line with the 2DS by 2050 is more than offset by fuel savings, resulting in net savings of USD 75 trillion.[2]

For emerging economies, access to international climate finance is essential. In the 2009-10 period, annual financial flows towards developing countries were between USD 70 billion and USD 120 billion (Clapp et al., 2012). By 2030, meeting these countries' needs will require investment between USD 140 billion and USD 175 billion (World Bank, 2009).

Governments alone cannot meet this level of investment. Unlocking private sector capital will be essential to achieve the desired objectives, but represents a substantial challenge: private investors are wary of the inherent high financial and policy risks of the low-carbon technology sector. Thus, a key tool is to use public funds to assume some of the risks the private market will not bear, and thereby leverage private investments.

Currently, low-carbon technology investment in OECD non-member economies is constrained by investor perception of high political and policy risks, coupled with macroeconomic instability. Investors will often rank emerging economies as having higher sovereignty risks than in OECD country markets, which drives up the cost of investment. Weak institutional track records, protective banking systems and risk-averse lending structures can hinder access to capital and liquidity, while high investment costs and incompatible prices, fossil fuel subsidies, and tariffs on low-carbon technologies can create significant economic and market barriers. These challenges will require emerging economies to put in place different investment strategies and revised market structures and business models.

In India, for example, high interest rates and short-term loans increase the cost of renewable energy projects by up to one-third compared with similar projects in the United States and Europe (Nelson et al., 2012). Funding constraints have hampered all stages of

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[2] Discounting the additional investment needs and the fuel savings at 3% and 10% would result in net savings of USD 29 trillion and USD 5 trillion, respectively.

the innovation process in India, particularly since the 2008 financial crisis. The government can help drive capital investment in low-carbon technologies through supportive policies such as grants, soft loans and tax incentives, and by building partnerships and networks with the private sector.

Across emerging economies, governments need to take the lead in establishing regulation, incentives and other policy measures that reduce the risk and unlock private finance. To counterbalance the higher financing costs associated with the capital-intensive nature of low-carbon investments, emerging economies will need to build capacity in reforming financing and regulatory spheres; this will be as critical to the transition as innovation in the energy sector itself.

For instance, China and Brazil have effectively used subsidised, low-cost debt to finance low-carbon technologies in their domestic markets. Contributions from national development banks (NDBs), national sovereign wealth funds, and national budgets or SOEs in these two countries now account for a significant portion of the world's low-carbon investment. The role of NDBs has become particularly important (Box 7.9).

Box 7.9 The role of NDBs in emerging economies

NDBs can fill the gap between public and currently low levels of private investment in low-carbon technologies – both complementing and catalysing private sector players. Unlike bilateral international agencies or multilateral development banks (MDBs), NDBs can capitalise on their knowledge, long relationships and proximity with the local private sector to better understand and address local barriers to investment. They can also provide long-term financing in local currency in local credit markets. Further, their activities and instruments can address both demand- and supply-side financing needs.

NDBs are already stepping into a lead role in climate financing: their annual clean energy investment rose from USD 39 billion in 2007 to USD 85 billion in 2013 (for a total of USD 509 billion over the period) (BNEF, 2014). Most of these investments were made in Europe (50%) and Asia (28%), with Central and South America a distant third (15%).

By country, Germany is the biggest supporter of the NDB role, with its Kreditanstalt für Wiederaufbau (KfW) investing most of the country's USD 191 billion deployed in the 2007-13 period (equivalent to 37.6% of all NDB investments). China comes in second with USD 98 billion in loans (19.2% of the total), mostly through its China Development Bank (CDB) and the Export-Import Bank of China (CEXIM). The Brazilian Development Bank (BNDES), with USD 54 billion invested (10.5% of the total), placed third.

It is worth noting that these NDBs' contributions significantly exceed those of big MDBs, such as the European Investment Bank (USD 58 billion) or the World Bank Group (USD 31.6 billion). MDBs do play a key role, however, in making funds available to OECD non-member economies that would otherwise have a hard time funding clean energy projects. Most NDBs focus on domestic lending, but the larger ones (e.g. BNDES and CDB) are increasingly financing projects in other countries (Global Commission on the Economy and Climate, 2014).

China and Brazil have taken the lead among emerging economies, in using NDBs for climate financing in developing countries; India and other countries are also considering these opportunities. New multilateral initiatives, such as the BRICS* New Development Bank (created in 2014), are also starting to appear to foster South-South investment in clean energy technologies.

* BRICS stands for Brazil, Russia, India, China and South Africa.

Emerging economies that lack access to long-term financing in local currency through local credit markets or through development banks (such as India and South Africa) are more reliant on multilateral banks, NDBs with international portfolios and bilateral development agencies (Global Commission on the Economy and Climate, 2014). One example of MDB efforts to catalyse climate finance in emerging economies is the ADB's Climate Technology Finance Center, which directly addresses barriers to technology deployment and diffusion in Asia and the Pacific. Recent OECD analysis shows that external development finance, whether bilateral or multilateral, has a positive and significant effect in mobilising private finance flows to developing countries, with a more pronounced effect in attracting domestic over international financial flows (Haščič et al., 2015).

Still, OECD non-member economies present other risks. Issues such as availability of reliable data, as well as shortages of skilled labour for designing, installing, commissioning and maintaining low-carbon energy technologies, as well as insufficient institutional capacity to facilitate decision making and implementation of policies and measures, also drive up the cost of financing. Subsidised finance can play an important role in bridging a finance gap but will not, in itself, reduce the underlying risk. The risks should be addressed through policy measures.

Exceptions do exist, however. Where resources and supply chains are favourable and low-cost finance is available, as is the case for onshore wind power in Brazil, renewable energy can already compete with fossil fuels. Lockheed Martin will construct the largest ocean thermal energy conversion power pilot plant developed to date in China, after negotiations for building the project in the United States failed for lack of finance (Strickland, 2013).

The role of key technologies

This section examines some key technology areas in both the supply and demand sectors in which emerging economies have significant potential and that are crucial for achieving the 2DS, emphasising the importance of advancing towards low-carbon energy sources while effectively managing the use of conventional technologies during the transition.

Moving towards renewable energy technologies

Renewable energy technologies can improve energy security and access to energy services, while also reducing dependence on fossil fuels and exposure to global market volatility, and contributing to environmental protection and climate change mitigation. They can also create jobs and strengthen the competitive edge of domestic industry. Emerging economies have recognised these benefits and stepped up their ambition to pursue various renewable energy technologies. In many cases, their natural resource endowments put them at a relative advantage for developing renewable energy sources – and indeed the technologies needed to optimise these resources.

Solar and wind power are garnering attention and seeing accelerated action. In 2013, China accounted for 21% of all global renewable investment (WRI, 2013), part of which translated into adding in excess of five times more wind and nearly twice as much solar as any other country (REN21, 2014). In fact, China attained global market leadership for both wind and PV (IEA, 2014b). In Brazil, onshore wind has been the lowest-cost source of new power capacity in recent long-term auctions for new electricity contracts, in competition with conventional technologies. Moreover, rooftop solar for homes is now competitive with Brazil's retail electricity prices (IRENA, 2012). In South Africa, wind power has been procured at costs as much as 30% below those of new coal-fired power (REN21, 2014; IEA, 2013c).

Further expanding the use of solar and wind power depends on successfully integrating these technologies into the overall electricity systems of emerging economies.

Plenty of other renewable energy sources are available for tapping in emerging economies. Great potential for geothermal power is evident in developing countries in Asia (particularly Indonesia), where abundant high-temperature hydrothermal resources have yet to be exploited. While considered economical, geothermal in these markets still requires mechanisms that address non-economic barriers to development and deployment.

In addition, emerging economies with abundant renewable energy potential should include mini-grid and off-grid solutions as possible approaches to expand energy access, and explore sustainable business models to promote these opportunities (Box 7.10).

Box 7.10

Expanding energy access through decentralised, low-carbon energy sources

With the international effort under way to achieve universal access to sustainable energy (through the UN Sustainable Energy for All initiative), there is increasing agreement about the huge opportunity available through decentralised solutions using renewable energy sources. Many renewable energy technologies, such as wind, solar power, small hydro and biomass, tend to be adaptable to smaller, modular and decentralised models that can be installed locally, at small scales.

In fact, the scenario for universal energy access by 2030 sees substantial shares of the additional electricity needed being generated and delivered by mini-grid (36%) and isolated off-grid (20%) solutions, with renewable sources providing more than 90% of the generation (IEA, 2011b).

Grid extension, based on the business model of conventional utilities (i.e. large-scale and centrally managed technologies), is the most suitable option for most urban zones and for around 30% of rural areas. While it is cheaper than mini-grid or off-grid solutions in such contexts, extending the grid to sparsely populated, remote or mountainous areas can be very costly and long-distance transmission systems tend to have high technical losses.

In some rural settings, the solution may evolve over time from off-grid to on-grid, as transmission and distribution systems begin to reach more remote areas. A key benefit in such situations is that renewable energy applied in mini-grid or off-grid systems can enable investments in future flexibility assets for grid-connected systems.

Mini-grid systems have already played an important part in rural electrification in China. Because design compatibility with the grid was considered, these assets should serve as an intermediate step to grid access (AGECC, 2010).

Investments encouraging low-carbon development and wider access to energy can contribute to poverty reduction, support climate change mitigation and stimulate economic activity. In all situations, it is important to explore sustainable business models that promote these opportunities.

Considering the role of nuclear energy

High rates of economic development and continued urbanisation are expected to drive up demand for electricity in emerging economies.[3] For some, this raises the question of whether to pursue nuclear energy as a means of meeting demand growth while reducing reliance on fossil fuels and emissions. Nuclear can be an attractive alternative to coal-fired

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[3] This subsection is based on the 2014 update of the IEA Technology Roadmap on nuclear energy.

power in some contexts, based on its economics, stable base-load operations and siting near main demand centres, combined with its environmental benefits. But governments must carefully consider factors such as energy and environmental policy, outlook for electricity demand, availability of energy resources, regulatory environment and power market structure.

China is the fastest-growing nuclear energy market in the world; its fleet includes technology developed nationally, as well as technologies transferred from Canada, France, Japan, Russia and the United States. Since its inception in the 1980s (first reactor began commercial operation in 1994), China's nuclear energy programme has evolved significantly. The last decade is marked by more rapid development of domestic reactor designs and supply chains, leading to an impressive transition from importing nuclear technology to developing and exporting local capabilities.

India began developing nuclear technology in the 1950s (first reactor began operations in 1969). Since the country is not party to the Treaty on the Non-Proliferation of Nuclear Weapons, development has been indigenous, with a strong focus on research and development. India has announced ambitious targets to increase the share of nuclear electricity in the coming decades, and could become the world's third-largest producer by 2040. Financing and public acceptance are substantial challenges, however, as is opening the Indian market to foreign investments and technology.

In the 2DS, China would see the largest increase in nuclear capacity additions – from 17 GW in 2014 to 250 GW in 2050, coming to represent 27% of global nuclear capacity and nuclear power generation. Nuclear energy markets would grow in India, the Middle East and Russia, whereas capacity is projected to either decline or remain flat in most OECD countries.

Changing the role of fossil fuels

Decarbonising the electricity systems of emerging economies is a daunting challenge in the 2DS. While electricity demand growth in OECD countries remains relatively flat (16% between 2012 and 2050), it skyrockets in OECD non-member economies – averaging 131% growth and as high as nearly 300% – driven primarily by emerging economies. Meeting this scale of increased demand will challenge the capacity of countries to deliver electricity in a clean, sustainable manner.

Globally, fossil fuels currently contribute to 82% to total primary energy supply (TPES). Fossil's share in TPES is particularly high in several emerging economies, such as South Africa (87%), India (81%) or China (88%). Brazil is an exception, thanks to its extensive hydro capacity.

One contributing factor is that many emerging economies have extensive fossil reserves, particularly coal, but also oil and gas. Using these resources may provide energy security benefits and access to affordable energy. Coal has been instrumental in lifting many out of poverty and providing access to electricity in China. It is likely to be used to bring energy access to large populations living in energy poverty in India (300 million) and in Southeast Asia (130 million). The share of fossil fuel technologies in electricity generation is higher in OECD non-member economies (74%) than in OECD countries (62%). Coal's contribution to electricity generation is particularly high in China (76%), India (71%) and South Africa (94%).

While generation from wind and solar technologies has grown annually at double-digit rates over the last ten years, electricity demand growth has largely been satisfied by fossil fuels. Between 2002 and 2012, coal accounted for 56% of the increase in electricity generation in OECD non-member economies. In the 2DS, coal's share in electricity generation is projected to decline over the next two decades in China, India and South Africa, but rise in parts of Southeast Asia, including Indonesia, Thailand, Malaysia and the Philippines.

China is actively moving to reduce its energy sector carbon intensity over the long term, primarily through a major expansion of its nuclear and renewable energy programmes. At present, China continues to expand its use of coal, although coal build has slowed recently due to a slight slowdown of the economy. Virtually all new coal plants are mandated to be large, highly efficient units, with the most recent 1 GW ultra-supercritical units having efficiencies around 46% (based on the lower heating value of the coal). China also has active programmes to improve the efficiency of its existing coal fleet, to retire ageing, less efficient coal units and, on carbon capture and storage (CCS), it has been a world leader in demonstrating aspects of CO_2 capture, CO_2 for enhanced oil recovery and CO_2 storage. As a result of the above efforts, China's carbon intensity is falling. Furthermore, the government has introduced increasingly stringent limits on emissions of air pollutants for new units from 2012 and on existing units from 2013.

Despite building up its renewable energy capacity, India still plans to forge ahead with building coal plants for the foreseeable future, predominantly driven by concerns of energy security, affordable energy, economic growth and greater electricity access. At present, the majority of coal plants under construction are subcritical plants, with low efficiency and high emissions, while some supercritical capacity has been built under its ultra-mega power plants programme. Policy guidance mandates that newly built plants from 2017 are required to be supercritical or better. A difficult policy and regulatory environment makes for slow progress on emissions and carbon intensity in India, which does not presently recognise CCS as a technology option. As in India, most of the new-build coal plants across Southeast Asia are currently subcritical.

Addressing CO_2 emissions from coal-fired plants at the global level requires concerted action. In some cases, switching to lower carbon generation should be pursued (e.g. to electricity generation from gas or non-fossil sources). On existing coal-fired plants, emerging economies should reduce and make efforts to eliminate generation from less efficient subcritical units and to increase generation from more efficient technology. New coal plants should exhibit high efficiency and low emissions. But taking such action is not always straightforward: though it is recognised that a more efficient plant may present lower average costs over its lifetime, its capital costs are generally higher; the ability to raise the initial capital generally determines the quality of the plant constructed. As many international lending banks have taken policy decisions not to lend against coal, builders are taking the lower-cost option, which leads to construction of less efficient, more polluting and climate unfriendly plants.

Once CCS technology has been suitably demonstrated, emerging economies should consider its deployment. In particular, South Africa's coal dependence and its geological resource for storage make CCS attractive for significant emissions reduction in the long run, and could allow fuller exploitation of the country's substantial coal endowment. The current approach towards CCS by Eskom (the state-owned power utility that produces almost all of South Africa's electricity) is to monitor research in OECD countries and undertake preliminary geological studies to assess the domestic potential for CCS. For now, this seems to strike the right balance in this particular context (OECD, 2013), since, at present, CCS technology is too costly to yet have a role.

Accelerating CCS deployment in these major economies is critical for achieving global low-carbon goals. The case can be made that OECD countries should consider providing support for CCS demonstration projects in emerging economies, where this technology can play a significant role in reducing the environmental impact of meeting increased energy demand or faces significant political or financial barriers.

Technology transition paths for end-use sectors

Buildings

Emerging economies account for a large share of anticipated expansion of the global building stock in the coming decades. Without action to improve energy efficiency, energy demand in the buildings sector is projected to increase by 77% in OECD non-member economies by 2050, with emerging economies accounting for 51% of the total increase. The main drivers include increases in household, residential and services floor area, higher ownership rates for existing electricity-consuming devices, and increasing demand for new products.

Given the long life span of buildings, opportunities to maximise energy efficiency tend to be larger and most cost-effective when energy and ecological considerations can be incorporated into new buildings. This makes policy action targeting new construction in emerging economies fundamental. Stringent energy building codes, minimum energy performance standards for appliances and equipment, and regulatory enforcement are especially important in fast-growing developing and emerging economies in the ASEAN, Brazil, China, India and South Africa, among others (IEA, 2013e). Equally important is the availability of human capacity and supportive infrastructure, including affordable energy efficient materials manufactured locally or regionally.

At the same time, several regions (e.g. ASEAN, India and South Africa) must make considerable effort to replace the inefficient use of traditional biomass with modern fuels and efficient cooking and water heating technologies, such as low-cost efficient biomass cook stoves and solar thermal technologies for water heating (IEA, 2013e). Progress in these areas is evident in China, which is the global leader in the use of solar thermal systems for basic water heating, and Brazil, which is installing solar water heaters in low-income housing (REN21, 2014). In parallel, emphasis on retrofitting existing buildings should be a clear policy focus for both OECD members and non-members (IAC, 2007).

Industry

Significant progress in improving energy efficiency and reducing CO_2 intensity in industry in recent years has been largely offset by the absolute growth in materials demand. Production of energy-intensive commodities, such as cement, is rising rapidly in most emerging economies where infrastructure and housing are being expanded at a fast rate.

Changes in energy-intensive industries, through adoption of BATs and greater penetration of less energy-intensive processes, can move these economies towards a low-carbon path. The potential to adopt newer and more efficient technologies delivers a large scope for productivity gains in production processes, which would help lower energy demand and emissions. Emerging economies together contribute 57% of total direct CO_2 emissions reductions seen in industry in 2050 the 2DS versus the 6DS.

In some cases, industries in emerging economies are already using the latest technology. Africa, for example, has some of the world's most efficient aluminium smelters and India is a leader in deploying efficient cement kilns (Box 7.11).

Transportation

By 2050, global passenger and freight travel is expected to double over 2010 levels, with OECD non-member economies accounting for nearly 90% of the increase. Anticipated growth in transport demand represents increased energy demand and CO_2 emissions, and poses energy security issues in many countries. But other factors come into play, including the need for substantial expansion of transport infrastructure (road and rail), particularly in emerging economies such as China and India. OECD non-member economies account for 85% of projected infrastructure additions over the next 40 years (IEA, 2013f).

Box 7.11

India cement industry: Moving towards world-best technology

Recent efforts to adopt BATs and environmental practices has made India's cement industry one of the most efficient in the world, and substantially reduced its carbon footprint. A shift away from inefficient wet kilns towards more efficient semi-dry and dry kilns, together with the adoption of less energy-intensive equipment and practices, has produced significant efficiency gains (Sathaye et al., 2007). The industrial average for total CO_2 emissions was reduced from 1.12 tonnes of CO_2 per tonne (tCO_2/t) of cement in 1996 to just 0.719 tCO_2/t cement in 2010.

Opportunities for further improvement still exist. India's cement technology roadmap sets out a strategy to reduce both energy demand and CO_2 emissions, largely by increasing rates of blending and alternative fuel/raw materials use, widespread implementation of waste heat recovery systems, and a radical step change in new technology development. Without appropriate measures in technology development and policy actions, CO_2 emissions from India's cement industry are projected to reach between 488 million tonnes of CO_2 ($MtCO_2$) and 835 $MtCO_2$ by 2050 – a massive increase from 137 $MtCO_2$ produced in 2010.

The technology roadmap is now being implemented at the plant level with support from the International Finance Corporation (IFC). On a larger scale, the roadmap supports India's ambition to enhance energy security by limiting growth in energy consumption by at least 377 petajoules, while also reducing direct CO_2 emission intensity by about 45% by 2050 (IEA and WBCSD, 2013).

Overall, the transport sector is decarbonising too slowly to reach the ambitious target of the 2DS in terms of transport electrification for light-duty road passenger applications (including cars and powered 2-wheelers). But recent progress in hybrid electric vehicles and electric vehicles (EVs) is noteworthy. China has been very proactive in promoting e-mobility, particularly through electric 2-wheelers, which were already cost-effective in 2013 (taking a societal point of view without discounting) (Box 7.12).

Recommended actions for the near term

Emerging economies will play a decisive role in the global transition to a sustainable energy system. To do so, they will need to use all technological options available, and find the most cost-effective way to deploy these technologies under country-specific circumstances.

Two initial challenges are, admittedly, somewhat daunting. First, governments need to identify priority technologies that can support national development goals while contributing to the global effort to transform energy systems. The second challenge is to decide whether to directly adopt technology from external sources, adapt such technology or develop their own technological solutions through domestic innovation. The more innovation capacity countries possess, the more likely they are to be able to optimise a pertinent technology portfolio, and to develop successful technology deployment strategies.

Energy resource endowments, governance and political frameworks, market policies and mechanisms, and the level of co-ordination among national entities will likely shape the approaches each country takes to low-carbon technology innovation. Technology roadmaps can be an effective tool to identify *who* can usefully do *what*, *when* and for *which* part of the innovation chain. Each country will need to create its own roadmap, and indeed a given technology may have diverse roadmaps depending on the context in which it is being taken up. Scaling up innovation of low-carbon technologies will require substantial and strategic action by emerging economies – often in collaboration with OECD countries.

Box 7.12 Radically transforming transport in China through e-mobility

China's potential to become a world leader in EV production is spurred by dependency on imported fossil fuels, increasing pollution from automobile production and higher vehicle ownership. Chinese consumers currently lead the way in adopting EVs. Thanks to technological improvements and favourable policy, China has the biggest fleet of battery electric bikes (e-bikes), with more than 150 million fully electric 2- and 3-wheelers on the road (accounting for over 50% of the 2-wheeler stock) (IEA, 2013d). Improvements in design and battery technology made the e-bikes desirable, while the highly modular product architecture of electric 2-wheelers resulted in standardisation, competition and acceptable pricing. Low purchase cost is the main driver for most users, together with high versatility in congested environments (IEA, 2014a). *ETP 2014* analysis showed that among EVs broadly, electric 2-wheelers offer the fastest payback period, particularly in urban contexts (IEA, 2014a).

Thanks to their high efficiency when running on electricity, deploying electric 2-wheelers also delivers carbon savings – even when electricity generation is carbon-intensive, as in most of China (IEA, 2014a). To further augment emission reductions, some large cities have aggressively promoted e-bikes, even to the point of eliminating the competition by banning gasoline-powered motorcycles. Shanghai, for example, banned gasoline-powered 2-wheeled vehicles in 1996 (IEA, 2011d).

China has 2 600 domestic plants that manufacture 36 million e-bikes annually, which can potentially support the Asian market (IEA, 2014a). The government has also enacted policies and programmes to promote EVs for passenger cars on a national scale. In 2012, China held the third-largest share of the global battery electric vehicle market, behind Japan and the United States, due in part to deployment of electric taxis in Shenzhen and Hangzhou (IEA, 2013d). A five-year Clean Air Action Plan (2013-17) for Beijing rules that of 600 000 new vehicles permitted, 170 000 should be EVs, plug-in hybrid electric vehicles or fuel-cell vehicles (IEA, 2014a).

In order to develop domestic innovation capacity that supports strategic technology deployment plans, emerging economies are encouraged to implement broad policy action to accelerate all stages of innovation across the range of priority low-carbon technologies. This includes strengthening local technological capabilities to adopt or adapt foreign technologies, or to develop technologies domestically. It also implies enhancing both technical and non-technical skills to create demand for technologies as they approach market-readiness.

To support capacity building and encourage local diffusion of developed country expertise and know-how, governments should consider opening their economies to foreign technologies by developing international trade and FDI, and reducing barriers that slow down the spread of technology. A key step towards these goals is establishing the political and socio-economic infrastructures, including regulatory and financial frameworks, and providing the supportive local investment climate needed to attract foreign investment. Setting up a solid IPR framework under which agreements can be structured is of critical importance.

As their own domestic actions will have a relatively low impact on global emissions reduction, OECD governments are encouraged to support emerging economy actions. International collaboration can help create demand for low-carbon technologies in emerging economies and also increase local capacity of governments and firms that acquire such advanced technology. For example, developed countries could share their knowledge about well-functioning support schemes and best practices, so that emerging economies can appropriately tailor policy support measures to encourage innovation and market development in their local context.

OECD countries could also focus the design of their domestic RDD&D to take into account applications and needs of emerging economies. They could invest in domestic innovation, strengthening their own systems for low-carbon innovation and thereby reinforcing their capacity to engage more effectively with emerging economies. To increase investment impact, OECD countries should consider supporting major low-carbon demonstration projects in emerging economies, especially if a given technology is expected to have large benefits (domestically and/or internationally) but faces significant barriers in the area that could deliver highest benefits.

Finally, developed countries should promote the flow of low-carbon technologies to emerging economies through diverse channels such as FDI, licensing and international trade. These approaches will boost incentives for firms to invest in further RDD&D targeted at emerging economies, confident of a higher potential return on their investment. They should also collaborate with emerging economies to provide multilateral solutions to finance low-carbon projects, particularly when countries lack long-term financing in local currency in their local credit markets.

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Chapter 8

Energy Technology Innovation in China

As it becomes more market-oriented in its continued pursuit of a resilient and sound economy, China is experiencing a substantial policy shift. Energy technology innovation, with a strong focus on clean energy technologies, is central to a strategy that faces head-on the dual challenge of satisfying energy demands while safeguarding the environment as part of China's self proclaimed "Energy Revolution".

Key findings

- ***Under the framework of the "China Dream", the Chinese government has set ambitious targets for sustained economic and socio-political development while adhering to "cultural inheritance, national security and ecological balance".*** *Behind the strategy, the government seeks to restructure its innovation systems and foster a more competitive enterprise system, with a focus on allocating and mobilising effective financing.*
- ***Rapid expansion of the energy system played a key role in China's sevenfold increase in gross domestic product (GDP), which lifted more than 400 million people out of extreme poverty.*** *From 1990 to 2012, China's primary energy demand increased more than threefold. As installed capacity expanded from 137 gigawatts (GW) in 1990 to 1 198 GW in 2012, electricity generation soared from 650 terawatt hours (TWh) to 5 024 TWh.*
- ***China's commitment to constrain its carbon dioxide (CO_2) emissions by 2030 – in part by setting a target that 20% of the primary energy mix will come from non-fossil sources – will help continue to drive energy sector innovation.*** *Recent energy policy and technology reforms seek to capture opportunities for economic advantage from the transition to a cleaner, more sustainable and increasingly market-oriented system. Parallel adoption of air pollution and environmental policies, along with measures to improve coal quality and generation efficiency provide additional incentives for clean energy innovation.*
- ***China's funding for research and development (R&D) as a proportion of GDP (R&D intensity) is increasing, but unprecedented co-ordination among government and institutional actors will be needed to sustain long-term innovation.*** *A comprehensive policy, regulatory and market framework is needed to set and track nationally relevant targets, facilitate feedback on innovative support policies, implement pricing and market reforms, and expand pilots, models and best practices.*
- ***To achieve its aim of being a global leader in low-carbon technology markets, China will need to strengthen its ability to innovate within and beyond its large state-owned enterprises (SOEs).*** *China has demonstrated its capacity to deliver original, integrated and optimised innovation; continued success will increasingly rely on joining and expanding international innovation networks, and harnessing their power to collaboratively transform domestic and global energy systems.*

Opportunities for policy action

- *China's dual targets for 2030 – to peak* CO_2 *emissions and to have non-fossil sources provide 20% of its primary energy mix – present an ambitious, stable policy environment, conducive to innovation. A transparent roadmap for innovation and technology financing is needed to support deployment of advanced technologies.*
- *Energy technology innovation that increases energy efficiency and security of supply in China is increasingly driven by policies focused on other challenges, e.g. reducing air pollution, saving water and water production technologies. Recognising where innovation policies could lead to multiple benefits would enhance long-term economic prosperity.*
- *In parallel with its 2030 targets, China needs to develop a more open and flexible policy framework that provides clear guidance on the transition to market-led efforts, with particular focus on encouraging new market entrants, especially small and medium-sized enterprises (SMEs).*
- *To both reward and protect innovators and emerging industry leaders, China needs to strengthen intellectual property (IP) laws, innovation incentives, rule of law, research guidance and R&D finance management systems. Better structures and improved transparency will make China more attractive to international players.*
- *To capture the economic benefits of this transition while also demonstrating its positive impacts on* CO_2 *emissions, and the environment in general, China will need to develop sound performance metrics, together with effective accounting, monitoring and enforcement programmes.*
- *Flexible policy guidance that sets clear benchmarks for performance can help to avoid system-wide lock-in of technologies and emissions, by encouraging greater competition, thereby avoiding a situation in which government alone is "picking winners".*
- *Chinese policy makers and enterprise leaders should consider global energy savings and global clean energy technology deployment aims when they set national targets and standards. They need to harness synergies and guide product development cycles with a view to promoting innovation and lower-cost technology deployment at both the domestic and global levels.*

The importance of energy technology innovation

Over the past two decades, China has experienced exceptional economic development. In the process of becoming the world's largest economy,[1] the country has lifted hundreds of millions of people out of poverty. To power this transformation, China tripled its primary energy supply. The government recognises that this process, driven by cost advantages and abundant indigenous coal resources, is not sustainable. In June 2014, President Xi Jinping called for an "energy revolution" to address the challenge to advance economic development and energy security while protecting the environment. Innovation in energy technology and systems will be crucial in meeting this challenge.

To ensure long-term economic prosperity while promoting green policies and low-carbon development, China is undertaking a transformation of its development and growth model. In 2013, under the newly appointed president, the Chinese government introduced a concept termed the "China Dream", which according to Xi is a framework for "unlocking China's

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[1] In 2014, according to the latest GDP estimates based on purchasing power parity (PPP) published in the International Monetary Fund's World Economic Outlook in October 2014, China would have become the world's largest economy. These projections already include the revised PPP data for 2011 released by the World Banks' International Comparison Program in 2014. The revised PPP data have not yet been incorporated into this year's *Energy Technology Perspectives (ETP)* scenarios.

creative and innovative forces to guide China's sustained economic and socio-political development – adhering to cultural inheritance, national security and ecological balance".

In practice, pursuing the China Dream requires long-term international co-operation, joining global networks that promote innovation in climate and energy technology. This chapter examines China's evolving innovation system and its critical role not only in realising an "Energy Revolution" but also in responding to the global climate and energy challenge.

A framework for an innovation-driven economic strategy

China needs to overcome the challenges of increasing constraints on resources, severe environmental pollution and deteriorating ecosystems. Clean energy innovation stands at the forefront of China's approach to overcoming these challenges, with its policy initiatives at the intersection of energy, climate change and economic prosperity. This innovation-driven strategy is set to play a key role in transforming China's development model, its economic structure, and its science and technology (S&T) agenda. It is likely to be complemented by a reallocation of resources through a mix of government planning and market forces. President Xi highlighted this comprehensive system approach in a speech to the Central Committee Financial Leading Group on 18 August 2014, entitled "To accelerate the implementation of an innovation-driven development strategy" (Xinhua Net, 2014), with four key points:

- to closely track global trends and scientific breakthroughs, providing direct guidance to domestic technology innovation … to build China's leadership and comparative advantage
- to strengthen incentives to retain and attract innovative talent … and formulate an entrepreneurial environment … especially in allocating capital
- to establish sound institutional mechanisms at key technological frontiers … to allow agencies, personnel, equipment, and funds to be actively engaged to promote technological innovation and key innovative enterprises
- to expand and strengthen international co-operation (and "going out")[2] to integrate into global innovation networks.

China's broad national innovation strategy includes the aim of helping to overcome domestic challenges by providing for a geographically and economically diverse population while meeting the expectations of an expanding urban middle class. The National Outline for Medium- and Long-Term Science and Technology Development (the National Outline) conceives of innovation as a powerful force for directly improving quality of life – not simply increasing average economic prosperity, but delivering tangible services, resources and opportunities to the public. The 11 S&T focus areas for the national innovation system were selected in light of Xi's four key points, and include energy, water and mineral resources, environment, agriculture, manufacturing, transportation, IT and modern services, population and health, urbanisation and city development, public security, and national defense.

The energy sector challenge

In a little over two decades, China's primary energy demand has increased more than threefold and its GDP sevenfold (Figure 8.1). Its installed power generation capacity expanded from 137 GW in 1990 to 1 198 GW in 2012, while over the same period electricity generation soared from 650 TWh to 5 024 TWh. This unprecedented growth was needed to fuel the transformation in China's economy and lift more than 400 million people out of extreme poverty (Wang, Gao and Zhou, 2006). China experienced double-digit growth

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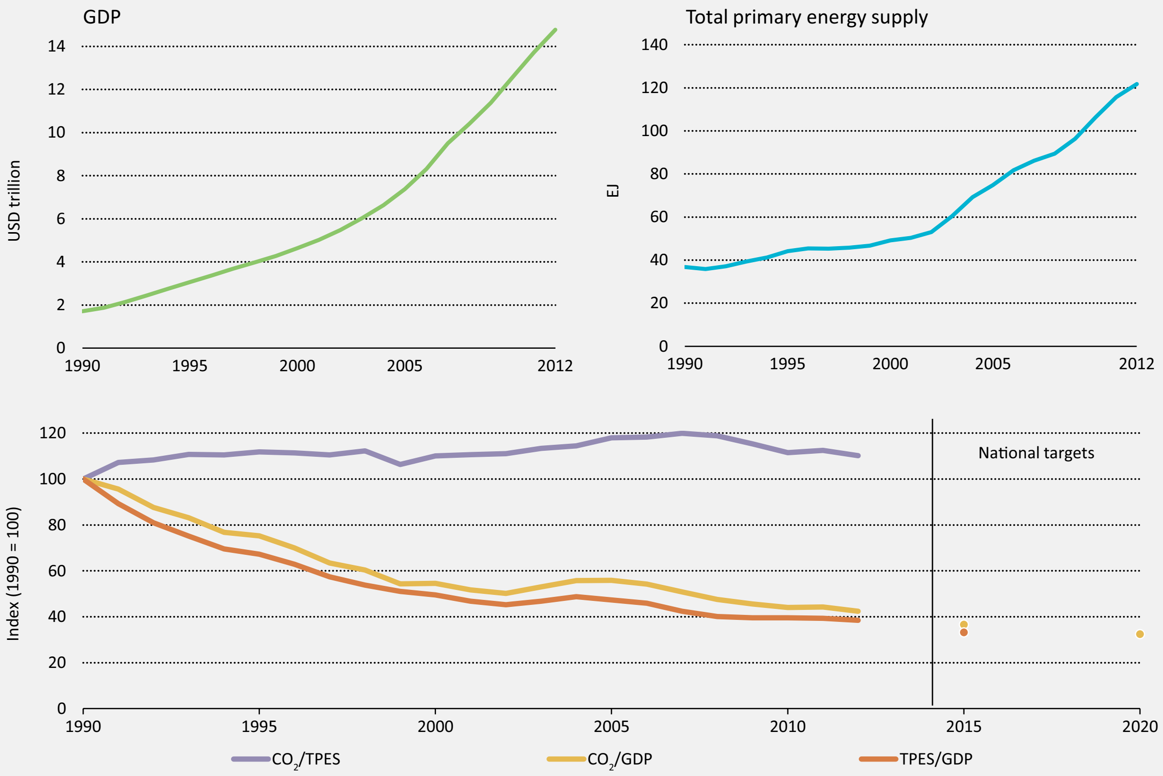
[2] China's "going out" strategy uses surplus capital to deepen its access to foreign markets, natural resources and advanced technology.

to 2010 and, though it has slowed recently to 7.4% in 2014, it is still high by international standards. While maintaining strong economic growth, planners in the world's most populous country recognise that they must also balance social concerns and protect the environment by developing strategic industries, enhancing S&T, and encouraging innovation.

Figure 8.1 China's historic GDP, primary energy supply, carbon intensity and targets



Notes: CO_2/GDP = carbon intensity of economy; TPES = total primary energy supply; TPES/GDP = energy intensity of economy; CO_2/TPES = carbon intensity of primary energy supply; GDP = USD2012 purchasing power parity. Figures and data that appear in this report can be downloaded from www.iea.org/etp2015.

Source: Adapted from IEA (2014a), *Energy, Climate Change and Environment: 2014 Insights*, OECD/IEA, Paris.

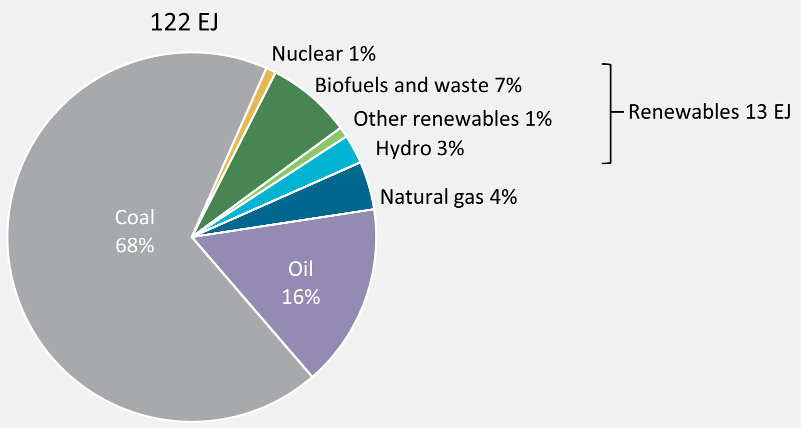
Key point *Energy technology innovation is increasingly important as China seeks to further reduce the carbon intensity of its energy sector.*

The preface to the National Outline demonstrates China's awareness of the daunting challenges it faces:

> "The nation's economic growth shows an excessive dependence on the consumption of energy and resources, with high associated environmental costs; the economic structure is irrational, characterised by a frail agricultural base and lagging high-tech industry and modern service industry; and firms lack core competitiveness and their economic returns are yet to be improved as a result of weak indigenous innovation capability. There are a whole range of problems concerning employment, distribution, health care, and national security that need prompt solutions."

The expansion in China's economy has been fuelled primarily by fossil fuels, particularly by coal (Figure 8.2). The contribution of fossil fuels to total primary energy demand rose from 76% in 1990 to 97% in 2000, before falling back to 88% in 2011. Coal's share of energy demand rose from 61% in 1990 to almost 70% in 2000, a level at which it has broadly remained since. Between 1990 and 2012, electricity generation rose almost eightfold; during that period, the share generated from fossil fuels fell from 80% to 78%, even though coal's share rose from 72% in 1990 to 76% in 2012. Over the last decade, more than 80% of the increase in global coal demand has come from China.

Figure 8.2 China's total primary energy supply in 2012



Key point *China's primary energy mix is dominated by fossil fuels.*

Relying on fossil fuels to such an extent presents China with several challenges: increased dependence on imports, declining energy security and increased fuel price volatility, alongside a need to shore up domestic transport and infrastructure bottlenecks. In recognition of the mounting contribution of fossil fuel use to local air, water and land pollution, and the escalation of water scarcity, sustainability has become a key theme of Chinese energy policy, principally since the beginning of the 11th Five-Year Plan (FYP) (2006-10) but notably since 2012.

In China's cities, high levels of sulphur dioxide, nitrogen oxides, fine particulates and volatile organic compounds damage human health, infrastructure and the environment. Fine particulates are particularly harmful. In January 2013, one-sixth of China's territory was subjected to a sustained period of severe air pollution during which the concentration of fine particulates in Beijing reached 40 times the exposure limit recommended by the World Health Organization (WHO). The Beijing Municipal Environmental Protection Bureau reported that major pollution sources included vehicles (31.1%), coal-fired power plants (22.4%), industry (18.1%) and dust (14.3%), with the remaining emissions from places, such as restaurants, other services and agriculture (Sina, 2014). In response, the Chinese government is facing growing pressure to put in place measures to combat pollution (Box 8.1). The implementation of these policies is at an early stage and will require robust systems to monitor compliance and demonstrate performance over large geographic and administrative areas.

Box 8.1 Addressing air pollution in China

China's air pollution levels have prompted regular campaigns to improve air quality in major urban areas. These campaigns, such as the one in the run-up to the 2008 Beijing Olympics, led to the closure and relocation of heavy industrial and coal-fired power plants within the Beijing municipality. Similar short-term measures were taken in preparation for the Shanghai World Expo in 2010. Additionally, urban areas have instituted stricter vehicle ownership and driving restrictions to limit vehicle emissions during periods of serious air quality hazards, while also building out more substantial public transport infrastructure such as the world's longest high-speed rail network at over 19 369.8 km as of 2014.

In particular, emissions of fine particles smaller than 2.5 micrometres (µm), referred to as $PM_{2.5}$, and smaller than 10 µm (PM_{10}) and other air pollutants have culminated in persistently high levels of smog. In Beijing, 25 days of January 2013 were categorised as unhealthy, very unhealthy or hazardous according to WHO air quality guidelines. This event, among others, spurred major policy shifts, including an announcement by Premier Li Keqiang in March 2014 that the government would immediately tackle $PM_{2.5}$ and PM_{10} levels with a "war on air pollution".

In 2013, China's State Council issued an Action Plan for Air Pollution Prevention and Control. The objective was to improve air quality and reduce air pollution, especially in three key regions: Beijing-Tianjin-Hebei, the Yangtze River Delta and the Pearl River Delta, for which different targets were set for improvement by 2017, with the Beijing region the most stringently targeted. Stated objectives are:

- For the three key regions, the annual average concentration of $PM_{2.5}$ should be reduced by 25% in Beijing-Tianjin-Hebei, 20% in the Yangtze River Delta and 15% in the Pearl River Delta.
- For all second- and third-tier cities, the annual average concentration of PM_{10} should be reduced by at least 10% from the 2012 level, and the number of days with clean air should be increased.
- For Beijing, the annual average concentration of $PM_{2.5}$ should be controlled at 60 microgrammes per cubic metre.

Policies that aim to reduce air pollution could have a significant impact on energy use and greenhouse gas (GHG) emissions, for example by reducing oil dependence or reducing the demand for coal in the electricity sector, both of which would lower the CO_2 emissions that exacerbate climate change. China's "war on air pollution" includes targets to reduce coal's share of power generation from 79% in 2011 to below 65% in 2017. Construction of new coal-fired power plants will be banned near the key urban areas of Beijing, Guangdong and Shanghai. Regional caps on coal use will also help reduce emissions. If these short-term actions are accompanied by longer-term structural reforms that also address leakage of carbon emissions and pollutants to surrounding areas, both long-term air quality improvements and emissions reductions are possible (IEA, 2014a).

Beyond air pollution the problem of water scarcity is one that is increasingly exercising the minds of those charged with energy system planning in China. The impacts of water pollution, increasing water consumption, freshwater withdrawals and expansion of water stress zones are major challenges. Large thermal power plants, whether nuclear, coal, gas, as well as, renewable energy from biofuels and technologies such as concentrating solar power (CSP) consume large quantities of water. For years, water shortages, water pollution, and flooding have constrained growth and affected public health and welfare in many parts of China (Xie et al, 2009). Particularly in the north, these problems are acute. There is a widening gap between water demand and limited supplies and, as a result of widespread pollution, water quality is deteriorating. Energy technology innovation and recognition of the interdependency of energy and water systems will be central to sustainable growth (Box 8.2).

Box 8.2 Water scarcity

While balancing energy consumption and supply, technology innovation and system improvement in pursuit of its proposed "Energy Revolution", China is pushing forward with water pricing reforms and stringent regulations and enforcement procedures targeted at water conservation. In the 12th FYP, targets were established to cut water consumption per unit of value-added industrial output by 30%. Water-related concerns are felt across China's energy sector, for example:

- Geography and geology exacerbate water resource availability in demand centres across large industrial belts and in China's northern cities. The majority of coal reserves lie inland in the Northwest region along with limited access to the quantities of water necessary for fossil fuel resource development, processing, conversion, combustion and cooling. This influences the technology choices and the projects approved by ministries, such as the National Development and Reform Commission (NDRC), as they seek to balance system-wide benefits with national infrastructure planning and demand from competing sectors, such as agriculture. Regardless of the energy mix, water availability and water quality will remain a long-term concern. A study on China's water risk suggests that by 2030, 87% of power plants will require some water to facilitate generation on a daily basis.
- There are public concerns over the exploration and production of unconventional gas, e.g. regarding the risk of leakage of hydrocarbons or chemicals during shale gas production. In the cases where water contamination has occurred, causes include factors such as poor sealing of the well casing, indicating a need for the enforcement of rigorous construction standards (IEA, 2014c).
- As prioritised in the 12th FYP, hydropower has been developed at a record pace with 60 medium and large-scale dams planned to come online by 2016 (China Water Risk, 2014). In 2014, construction of China's 13.86 GW Xiluodu hydropower station was completed, the country's second-largest facility in terms of capacity, quickly followed by two other major dam projects. As China develops its hydropower resources, it has a challenging task to balance environmental and social trade-offs with alternative generation sources.
- China has plans to construct desalination plants as it seeks to secure water supplies for many of its coastal cities, including Tianjin and Qingdao. As desalination is an energy-intensive process for water production, expansion of this technology will increase the demand for energy (Lehane, 2014).

Additionally, while coastal projects that incorporate saltwater cooling will offset the need for fresh water, water treatment and energy storage facilities will further impact China's water-energy resource challenge.

Progressing carbon intensity and climate targets

Targets set in successive FYPs demonstrate China's recognition, at the highest political levels of the need to mitigate climate change. Its 11th FYP aimed for a 20% reduction in energy consumption per unit of GDP between 2005 and 2010. A reduction of 19.1% was achieved, offsetting emissions of 1.46 gigatonnes of CO_2 ($GtCO_2$) (China's Central Government, 2011).

China has also established a long-term target to reduce CO_2 emissions per unit of GDP by 40% to 45% by 2020, compared with the value in 2005 (Figure 8.1). Announced in 2009, this is a mandatory indicator for national economic and social development. Since the 11th FYP, China has broadly been on course to meet this target. In the energy sector, effort has been directed at improving energy conservation and energy efficiency, with China generally on track to reduce CO_2 per unit of GDP by 17% between 2010 and 2015, and energy intensity by 16%. CO_2 emissions per unit of GDP in 2013 were 4.3% lower than in 2012, and 29% lower than in 2005, equivalent to a cumulative reduction of 2.5 $GtCO_2$ (NDRC, 2014). China's recent Work Plan for Controlling Greenhouse Gas Emissions during the 12th FYP is an important guidance document assigning carbon intensity reduction targets to all provinces, autonomous regions and municipalities.

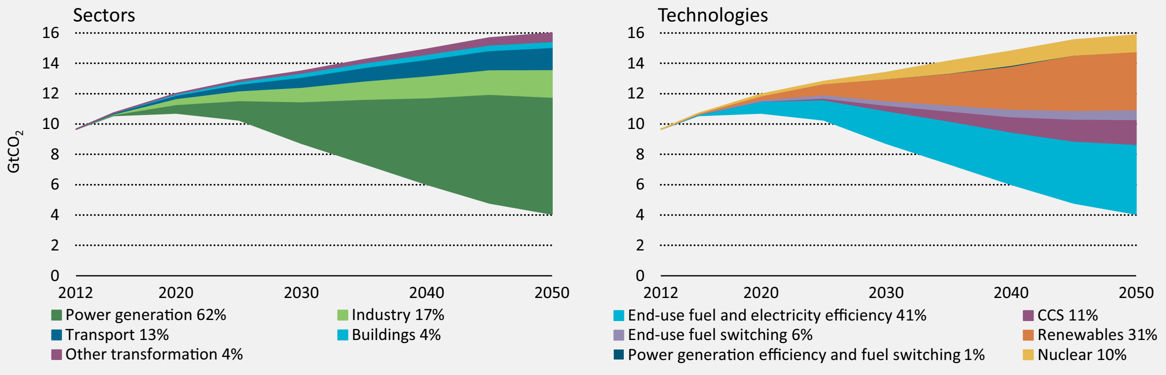
The carbon intensity of China's electricity generation has been significantly lowered from 894 grammes of CO_2 per kilowatt hour (gCO_2/kWh) in 1990 to 734 gCO_2/kWh in 2012. The effort to cut the energy sector's CO_2 emissions is and will remain a central theme in addressing climate change. Yet a growing commitment to reducing the carbon intensity of the energy sector has led to a major emphasis on non-fossil energy for power generation, prompting deployment of the world's fastest-growing fleets of wind, solar and nuclear power stations. In November 2014, China announced jointly with the United States a target to reach peak GHG emissions by 2030 and to make non-fossil energy 20% of the primary energy mix by the same year (White House, 2014), though the exact emissions level has not yet been stated. More recently, caps to 2020 were set at 4.8 billion tonnes of coal equivalent annual primary energy consumption (translating to an annual growth of 3.5%) and at 4.2 billion tonnes annual coal consumption.

Targeting 2020 and beyond

As China moves towards implementing its 2020 carbon intensity targets and the 2030 targets jointly announced with the United States, identifying the necessary long-term energy metrics, implementation and guidance will help to frame appropriate short-term policy and technology responses. China's emissions reduction potential will have a significant impact on global emissions reduction outcomes.

For *ETP 2015*, the IEA used modelling techniques to analyse and compare possible energy scenarios, with its main global scenarios being the 2DS, 4DS and 6DS.[3] The scenarios for China are elements of these global scenarios based on least-cost mitigation, where CO_2 emissions are priced uniformly around the globe. Projections from the scenarios should not be confused with predictions or forecasts, or even recommendations that China should or could commit to such a path. An equitable burden-sharing of the efforts to mitigate climate change is unlikely to be similar to a cost-effective distribution of efforts. *ETP 2015*, in its 2DS, sets an ambitious scenario for China, reducing annual emissions by over 10 $GtCO_2$ by 2050 compared with business as usual (Figure 8.3).

Figure 8.3 Contributions to China's emissions reductions to achieve the 2DS



Note: CCS = carbon capture and storage.

Key point *Power sector technology innovation, energy efficiency and renewable energy deployment are critical in the 2DS to reduce China's annual emissions of CO_2 to 4 Gt by 2050.*

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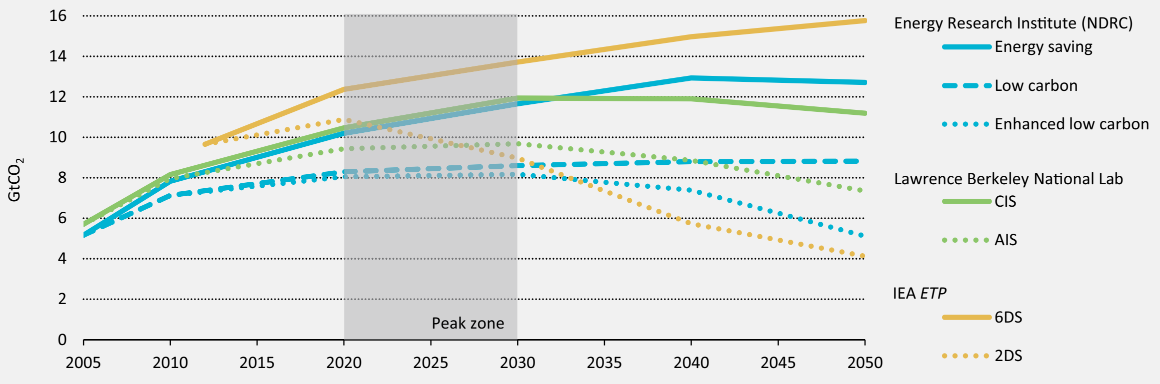
[3] The *ETP 2015* scenarios are described in Chapter 1, Global Outlook, Box 1.1.

Based on the 2DS, to cut CO_2 emissions by half compared with 2012 levels would be an enormous challenge for China. Almost 50% of these CO_2 reductions are achieved in the power sector by increasing efficiency, switching from coal to gas, increasing the contributions from nuclear power and renewable energy technologies, and deploying CCS. In industry, reductions arise from improved process efficiency, fuel switching and, again, deploying CCS. Further reductions would be sought from the other end-use sectors. To achieve very demanding targets for 2050, it would be essential that appropriate measures were put in place to 2020 to set China on the path to a lower carbon future.

An array of long-term scenarios (Figure 8.4) projects trajectories for China's CO_2 emissions to 2050. China's enhanced low-carbon scenario, Lawrence Berkeley National Laboratory's continuous improvement scenario (CIS) and accelerated improvement scenario (AIS), and *ETP*'s 2DS peak between 8 Gt and 12 Gt prior to 2030, representing options for peaking that are currently consistent with the United States-China joint statements. If no new policies were to be implemented, *ETP*'s 6DS suggests that China's emissions could reach 12 Gt by 2020 and 16 Gt in 2050.

Figure 8.4 Comparison of long-term scenarios in context of China's 2030 emissions peak



Notes: CIS = continued improvement scenario; AIS = accelerated improvement scenario. *ETP* scenarios include energy and process-related CO_2 emissions.

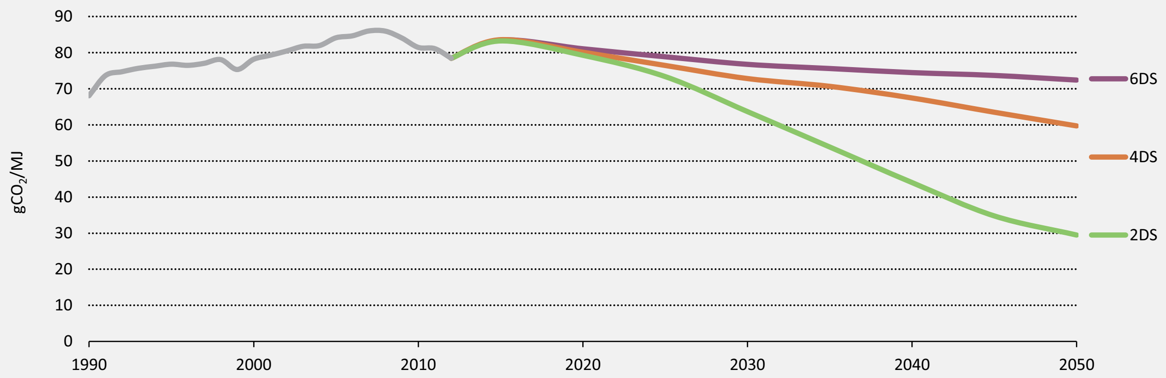
Sources: Li, H. M. and Q. Ye (2011), "Comparison of China's carbon emission scenarios in 2050", *Advances in Climate Change Research*, Vol. 2, National Climate Center, Beijing, pp 193-202; Zhou et al. (2013), "China's energy and emissions outlook to 2050: Perspectives from bottom-up energy end-use model", *Energy Policy*, Vol. 53, Elsevier, Amsterdam, pp 51-62.

Key point *Divergent low-carbon scenarios demonstrate a range of trajectories while still peaking between 2020 and 2030, consistent with China's emissions peak target.*

China's 40% to 45% reduction target by 2020 puts it on track to reduce emissions that are roughly consistent with the 2DS within the same time frame. Non-fossil energy targets of 15% of the energy mix by 2020 have been pursued, which also correspond closely to the non-fossil targets projected in the 2DS. While China anticipates that its CO_2 emissions will peak around 2030, it recently announced it will strive to reach that peak sooner. This peak is, however, still likely to be later than shown in the *ETP* 2DS, in which China's emissions must peak by 2020, implying the need for a more stringent regime for China to meet 2DS targets by 2050. Significantly, China is taking additional actions to manage CO_2 emissions, such as increasing afforestation and strengthening the management of forests; the forest area is targeted to increase by 40 million hectares by 2020 over levels in 2005.

To meet 2DS targets, aggressive and globally relevant improvements in energy efficiency are needed, as well as a steep drop in carbon intensity (Figure 8.5).

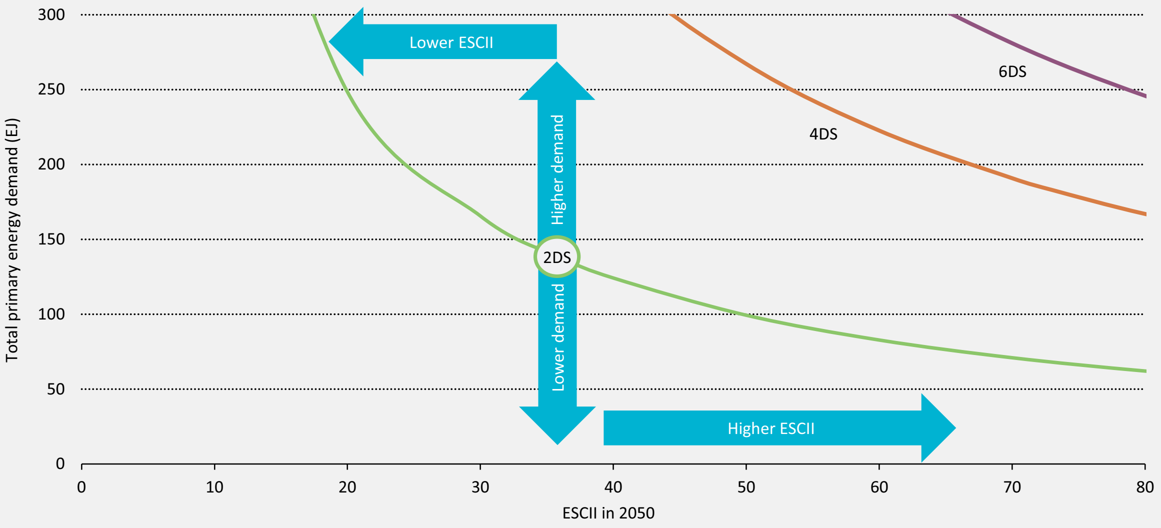
Figure 8.5 China's carbon intensity in long-term IEA scenarios



Key point *While the carbon intensity of China's energy sector has declined recently, a marked downward trend will need to continue to achieve the 2DS.*

In China and other countries with rapid growth, significantly increasing energy demand provides a unique opportunity to shape the future energy system, but also a danger of long-term energy infrastructure lock-in. There is an interplay between energy demand and supply: the higher the demand is in 2050, the cleaner the energy supply needs to be (i.e. a lower ESCII value) to deliver a given greenhouse gas emissions outcome (Figure 8.6). The emissions reduction challenge becomes more difficult in areas of high energy demand if more immediate action to decarbonise and opportunities to accelerate innovation are lost.

Figure 8.6 Trade-off between reducing carbon intensity and reducing energy demand for China



Note: EJ = exajoules.

Key point *High long-term energy demand will require significantly reducing carbon intensity in the short term.*

Why now is a good time for action on innovation

China has developed a series of working plans and working division schemes with three key areas of drivers for action: industrial transformation, energy system optimisation, and energy efficiency and the environment (Box 8.3). The interaction of the cross-cutting policies to address these objectives creates China's top-down policy environment and existing framework for innovation.

Industrial transformation includes upgrading traditional industry and promoting strategic emerging industries (SEIs). A key dual focus is transitioning away from energy-intensive and heavily polluting industry on the demand side while also boosting efficiency and shifting from high-emission to lower-emission fuel sources for energy supply. Technologies and industries are supported that promote greater energy efficiency and conservation, and increased environmental benefits, such as alternative energy vehicles. Such implementation heavily relies on stimulating the service industry, eliminating outmoded production capacity and scheduling clear targets. Such measures have included notices on eliminating "backward" production capacity across 19 industries; and closure of small, "backward" coal mines.

Of course, transitioning away from energy-intensive and heavily polluting industry may be achieved in different ways. China could follow the example that developed nations have occasionally taken and simply export it to countries where environmental standards are less strict – and this will happen in some cases. Ideally, however, manufacturers in China will focus on technological innovations that enable major reductions in energy consumption, e.g. taking advantage of advances in engineering, materials, sensors and controls, and information technologies that have the potential to transform industrial processes.

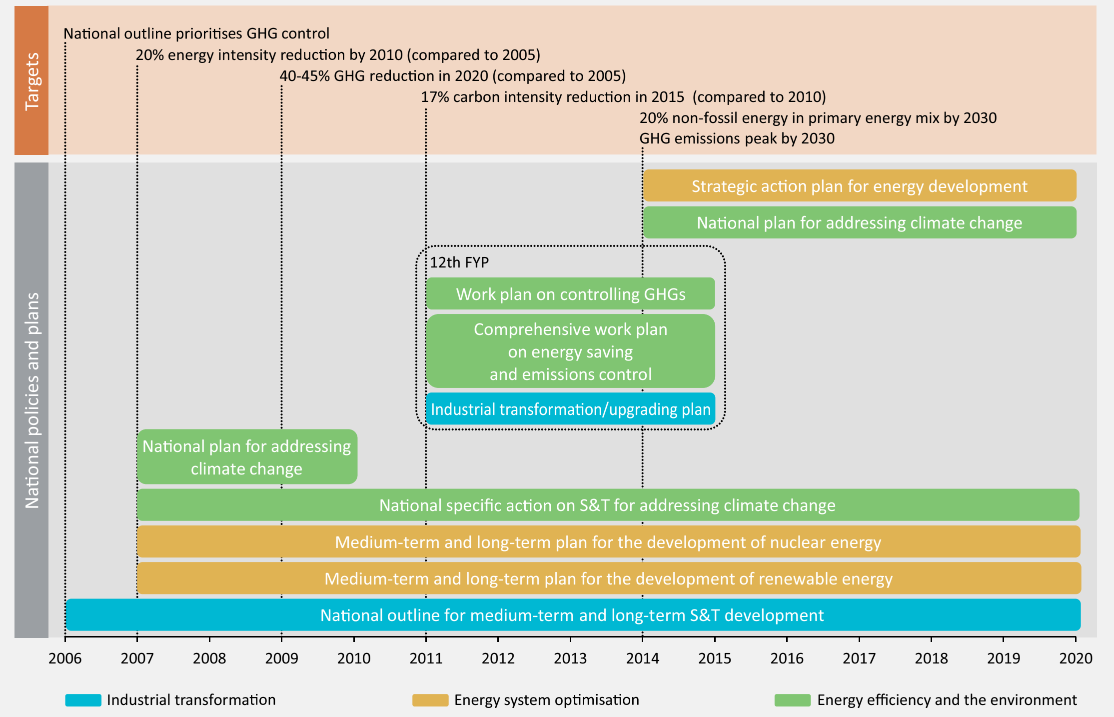
Energy system optimisation includes improving energy and fuel pricing systems across supply and demand infrastructure, with the main focus on cleaner utilisation of fossil energy and promotion of non-fossil energy technologies. For renewables, recent measures continue to promote the photovoltaic (PV) industry and improve methods for managing and financing distributed generation. Recent measures have included encouraging coalbed methane and shale gas developments to augment the share of natural gas in the energy mix. In 2013, coalbed methane production totalled 13 billion cubic metres (bcm), double that in 2009 (MLR, 2014a), while shale gas production expanded eightfold from 2012 to 2013, reaching 200 million cubic metres (MLR, 2014b). Additionally, in 2014, a joint notice from the National Energy Administration (NEA) and the Ministry of Environmental Protection (MEP) promoting biomass-fuelled boiler demonstration projects was seeking to expand the role of low-carbon energy.

Efforts to boost **energy efficiency and the environment** are being incorporated throughout the research, development and commercial deployment phase of new energy technologies and products. New technologies and products are being developed, energy services enhanced, and the economic, environmental and political costs of energy access and provision identified and reduced. For instance, in 2012, China carried out the "One Hundred Energy Efficiency Standard Promotion Projects" programme to initiate, update and publish energy efficiency standards and energy auditing guidelines for heavy industries, and compile benchmarking indicators for energy-saving products. Over 48 national energy-saving standards were published in 2013, with a total of 105 standards in 2012 and 2013. Additionally, since the end of 2013, as a result of the national action plan on green building, labelling green construction materials and compliance with national standards of energy performance in all new buildings has been mandatory. Other measures include: action plans on prevention and control of air pollution in Beijing-Tianjin-Hebei and in other low emissions zones; an action plan for energy conservation and emissions reductions from coal-fired power plants (2014-20). China has also issued a notice on low-carbon transportation across one thousand firms (auto, ship, road and ports).

Box 8.3 Key drivers for national policy frame China's innovation environment

Over the past ten years China has developed a range of nationally determined guidelines and policies to address critical issues in the nation's development. In the context of innovation and more specifically S&T, these policies are driven by the three policy objectives of promoting **industrial transformation**, securing **energy system optimisation** and strengthening **energy efficiency and the environment**.

Figure 8.7 Cross-cutting national energy, climate and S&T policies



Key point *China's top-down but cross-cutting policy environment, shaped by key objectives and drivers, creates the national innovation framework.*

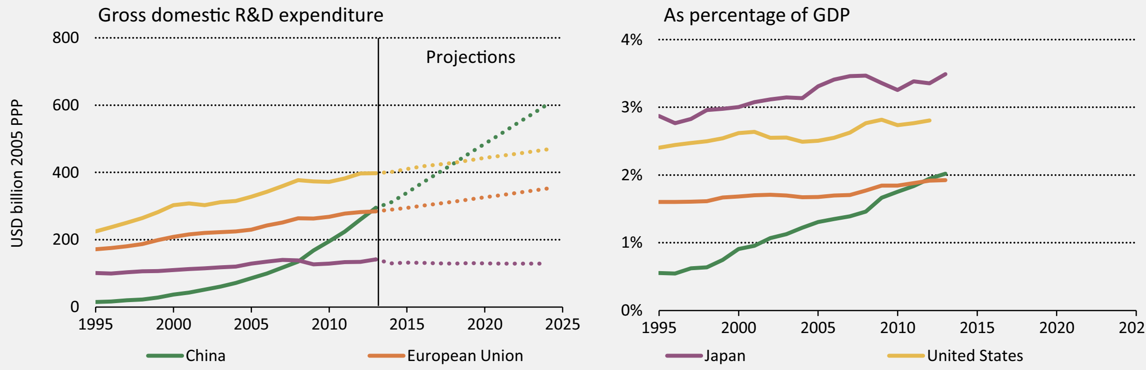
In 2013, such national plans, regulatory and policy measures have led to outcomes including: USD 2 billion of emerging industry investment funds in the area of energy conservation, environmental protection and new energy; the closure of 4.47 GW of small thermal power units; non-fossil primary energy achieving a share of 9.8%; USD 515 million spent on energy savings; and carbon emissions intensity per unit of GDP reduced to 28.56% based on 2005 levels.

In particular, policies and measures, such as the 2010 China State Council declaration for a "Decision on Accelerating the Development of Strategic Emerging Industries", have created a positive atmosphere for the progress of research, development and demonstration (RD&D) into emerging technologies, along with development of environmental protection measures. This will influence progress in electric vehicles (EVs) and on renewable energy technologies such as large-scale wind turbines. However, as China further integrates into global technology markets, market-oriented policies rather than command-control instruments are needed to encourage wider benefits of industrial transformation, energy evolution and China's response to climate change and environmental protection.

China's innovation in the global and OECD context

In 2012, China's R&D intensity – its R&D funding as a proportion of GDP – matched that of the European Union (EU) for the first time. Perhaps more significant is the rapid rate of advance: from 2000 to 2012, China's funding for S&T doubled from 0.9% to 1.98%, while EU funding rose more modestly from 1.74% to 1.98%. China's R&D intensity climbed to 2.08% in 2013, with funding of USD 192 billion, up USD 25 billion from 2012, with enterprises accounting for 76.6% of the total R&D spending (NBS, 2014a). Based on projections from the Organisation for Economic Co-operation and Development (OECD), this trajectory is likely to continue to 2020 with China overtaking the United States, the present global leader in R&D, by 2019 (Figure 8.8). In contrast with China's rising share of global R&D, which has more than doubled since 2002, the United States' share has decreased by 20% over the same period (Foreign Policy, 2014). In terms of PPP, the total IEA member country R&D public investment in the energy sector in 2011 was USD 17 billion compared to USD 301 billion in public sector investment across all R&D areas.

Figure 8.8 China's total R&D spending and OECD projections



Source: OECD (2014), *OECD Science, Technology and Industry Outlook 2014*, OECD Publishing, Paris.

Key point *China is poised to become the global leader in R&D spending by 2019.*

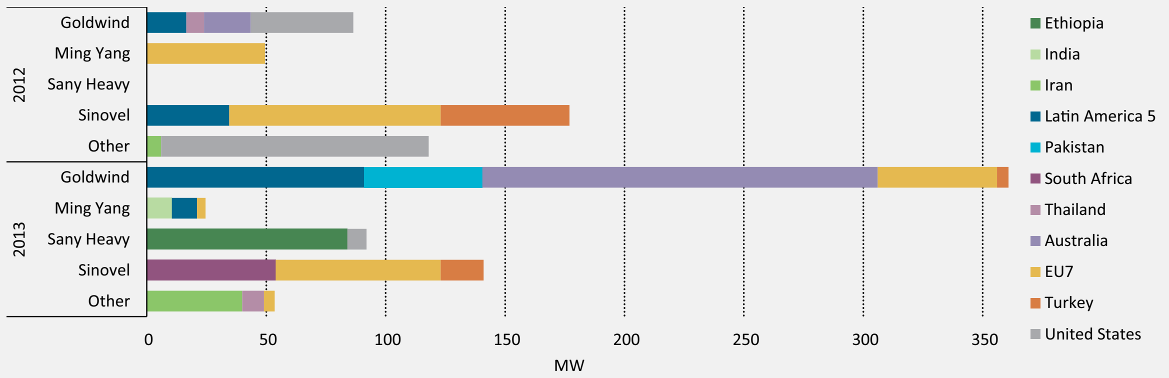
As the world's largest manufacturer, China's economic development has significant implications for global technology deployment. For example, global exports of domestically manufactured wind turbines increased by 65% between 2012 and 2013, not only to developing and emerging economies but also to competitive wind markets in countries such as the United States and Australia (Figure 8.9).

While China's manufacturing base and technology deployment have been evolving from "low-cost, made in China" to "designed and made in China" and "deployed in China and beyond", they will face significant constraints, including:

- the pace at which domestic demand for clean energy technologies will drive home-grown innovation

- the response of China's innovation centres and domestic policy to the impact of global competition
- the willingness of China's key industries and local governments to cope with the inevitable growing pains and seize opportunities.

Figure 8.9 Chinese wind turbine exports by company and destination



Notes: MW = megawatt; Latin America 5 = Bolivia, Brazil, Chile, Ecuador and Panama; EU7 = Bulgaria, Denmark, Finland, Italy, Romania, Spain and Sweden. Sany Heavy Industries had no exports in 2012.
Source: Adapted from IEA (2014b), *Medium Term Renewable Energy Market Report 2014*, OECD/IEA, Paris.

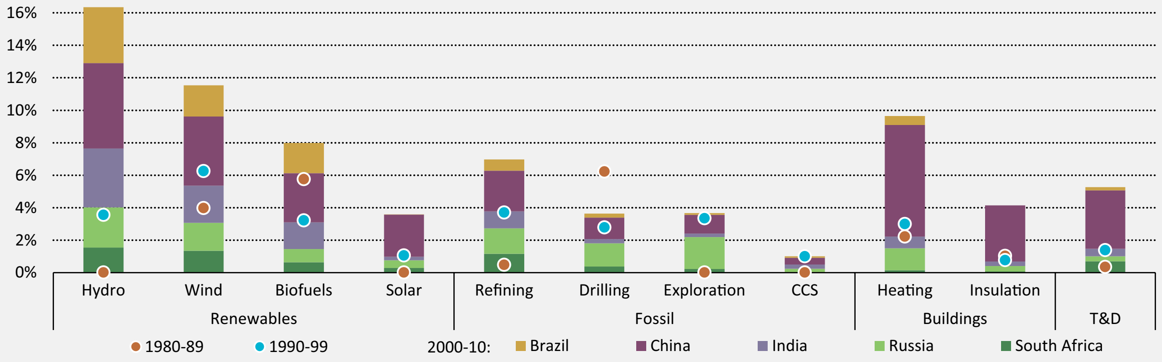
Key point *In 2012/13, Chinese exports of wind turbines, including advanced turbines for deployment offshore, increased significantly across a wide range of countries.*

This move up the value curve can be further demonstrated by looking at China's contributions to global patent development. (Note that, while the number of patent applications offers a measure of technology innovation capacity, it provides no indication of their quality.) From 2000-10, the growth of patent applications across energy technologies and specifically renewable energy experienced a remarkable increase (Figure 8.10). A large share of the growth took place in China, especially in wind power, heating, insulation, solar power, and transmission and distribution (T&D).

Growing innovation capacity and technology deployment, within and among emerging economies, along with increasing investment flows between them, are creating new, reciprocal opportunities (Box 8.4). Between 2005 and 2012, for example, the Brazilian energy sector absorbed USD 18.3 billion worth of investments from China (IEA, 2013). China also announced at the Rio+20 Conference in 2012 that it would contribute USD 3.25 billion to a three-year South-South initiative on climate change. Under the initiative, 900 000 energy efficient lights and more than 10 000 energy efficient air conditioners are being donated to African countries.

The intensification of such innovation can result in a rapid deployment of clean energy technologies in emerging economies and contribute to South-South partnerships, offering new avenues for climate mitigation (see Chapter 7). However, if emerging economies work together exclusively, it may reduce competitiveness, while also increasing heterogeneity in global technology standards. The result may inhibit innovation and global diffusion of technology.

Figure 8.10 Emerging economy patent applications as percent of total IEA



Source: IEA (2013), *Energy Investments and Technology Transfer Across Emerging Economies: The Case of Brazil and China*, Partner Country Series, OECD/IEA, Paris.

Key point *Emerging economy patent applications are rapidly increasing, with China leading across several clean energy technologies.*

Box 8.4 Technology transfer opportunities and challenges

As China continues to move up the value chain in advanced technology and innovative systems, challenges and opportunities brought on by the shifting global technology transfer landscape will affect both the import and export of technologies from China. These have the potential to shape enterprise growth and public objectives in different ways, and in a different sequence depending on the technology and enterprise status, business model, international partnerships and market exposure of China's technology players.

Opportunities:

- greater global and domestic diffusion of cost-competitive low-carbon technologies
- commercial opportunities for increasingly global enterprises and multinational corporations alike
- local SMEs benefiting from knowledge transfer from global partnerships
- local technologies benefiting from global innovation networks and licensing frameworks
- faster infrastructure build-out and avoiding long-term emissions lock-in
- opportunity to establish innovative first-of-a-kind market and system design relevant for the local context
- developing a healthy and sustainable competitive technology ecosystem.

Challenges:

- local content provisions creating bottlenecks to trade, quality and cost competitiveness
- increasing heterogeneity in global standards causing impediments to technology interoperability, specifically in (but not limited to) the context of smart grid build-out and EVs
- difficulty in building timely institutions to promote stable financing and technical and regulatory systems
- exposure to global market fluctuations, policy developments overseas, and legal and trade disputes
- IP infringement.

China's system: Finding equilibrium and innovation opportunity

China's innovation policy framework and institutional decision-making structures are multi-layered. After the central government formulates general guidance and principles, subordinate ministries develop detailed policies, which provincial and local governments bear the responsibility of implementing. Generally, the financial input and oversight for policy implementation is shared between central and local government authorities, which often follows the direction of central government allocation. This process often leads to overlapping jurisdictions that may be advantageous or disadvantageous for innovation (Figure 8.11). A framework to ensure effective oversight and to streamline functions is necessary to improve fund allocation and the monitoring and evaluation of performance.

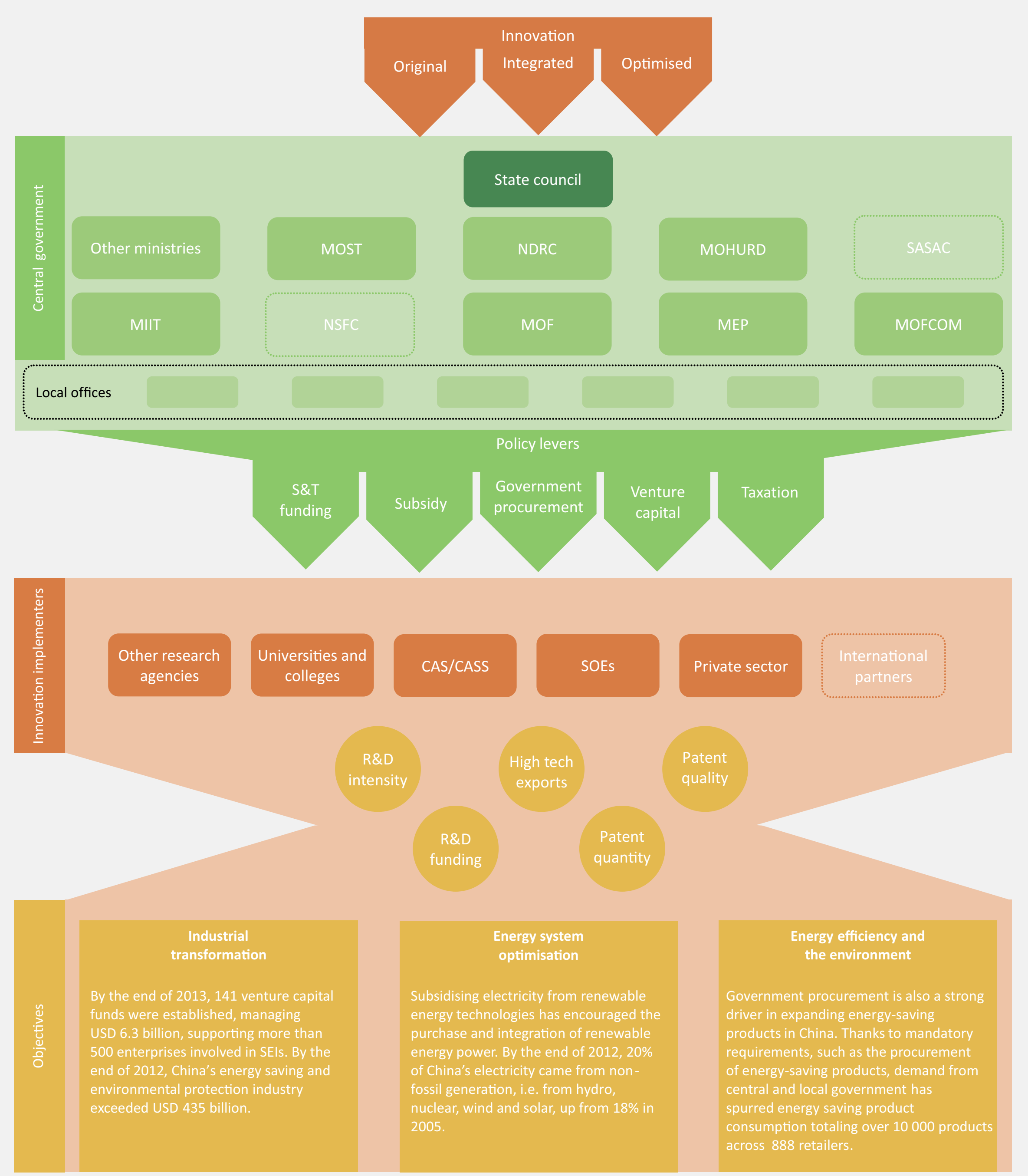
During the 11th FYP period (2006-2010), cutting energy intensity was a core element of energy policy, with China reducing its energy consumption per unit of GDP by 19.1% against a target of 20% (China's Central Government, 2011). Central government policies that aim to lower carbon intensity provide opportunities to set targets and timetables for energy efficiency and emissions reduction at the local level. In parallel, the central government has gradually linked efforts to address environmental challenges with opportunities to create market systems while showcasing local approaches to transforming development and the economic structure. However, co-ordinating the low-carbon development efforts of central and local governments has been a challenge. Regional competition to raise GDP may lead local governments to rely on large industrial and infrastructure projects to enhance local economic capacity and expand tax revenue, even though many such projects increase energy consumption, pollution and CO_2 emissions.

To help implement national plans, the NDRC, relevant ministries and local governments issued further detailed policies. A system of assessment was established to help the central government monitor and assess the effects of energy conservation and emissions reduction measures. In addition, incentives were used to encourage co-operation by local governments and enterprises, including appraisal and promotion of local government leaders, funding and approval of the construction of energy-intensive projects, and variations in end-use power prices.

A clear GHG control target was established during the 12th FYP period (2011-15), together with a national working plan for controlling GHGs, including carbon intensity reduction targets in all provinces, autonomous regions and municipalities. Targets were linked to the continuation and expansion of the objective responsibility system, a performance management system for local government officials. The levers of low-carbon policies were extended to transforming traditional industries, eliminating inefficient production capacity and supporting SEIs (Box 8.5). The policies also sought to enhance the development of the service industry, and promote cleaner fossil fuels and non-fossil energy technologies. To promote energy-saving technologies, products and SEIs in general, policies were introduced to enhance evaluation, GHG accounting, and energy efficiency standards and labelling.

To relieve regional GDP competition and unify central government objectives and local government actions, the national government has set about improving its performance appraisal indicator index by replacing total GDP by "Green GDP", emphasising the quality of GDP over quantity. Hence, regional actions on carbon emission control and environmental protection are linked with local governments' performance. Meanwhile, in 2013, to further unlock the command-control constraint and incentivise private sector players, the central government cancelled or reduced its administrative authority in over 400 approval areas with the aim of institutional decentralisation (减政放权，jianzheng fangquan). Accordingly, local government would shoulder greater responsibility and enjoy more autonomy while accepting higher risk.

Figure 8.11 Overview of China's innovation landscape



Industrial transformation

By the end of 2013, 141 venture capital funds were established, managing USD 6.3 billion, supporting more than 500 enterprises involved in SEIs. By the end of 2012, China's energy saving and environmental protection industry exceeded USD 435 billion.

Energy system optimisation

Subsidising electricity from renewable energy technologies has encouraged the purchase and integration of renewable energy power. By the end of 2012, 20% of China's electricity came from non-fossil generation, i.e. from hydro, nuclear, wind and solar, up from 18% in 2005.

Energy efficiency and the environment

Government procurement is also a strong driver in expanding energy-saving products in China. Thanks to mandatory requirements, such as the procurement of energy-saving products, demand from central and local government has spurred energy saving product consumption totaling over 10 000 products across 888 retailers.

Notes: CAS = China Academy of Sciences; CASS = Chinese Academy of Social Sciences; MIIT = Ministry of Industry and Information Technology; MOF = Ministry of Finance; MOFCOM = Ministry of Commerce; MOHURD = Ministry of Housing, Urban and Rural Development; MOST = Ministry of Science and Technology; NDRC = National Development and Reform Commission; NSF = National Science Foundation; SASAC = State-Owned Assets Supervision and Administration Commission of the State Council.
Source: NDRC (2013), *China's Policies and Actions for Addressing Climate Change 2013*, NDRC, Beijing, http://en.ndrc.gov.cn/newsrelease/201311/P020131108611533042884.pdf.

Key point *China's innovation policy framework and institutional decision-making bodies are made up of a top-down but complex system in the process of reform.*

Box 8.5 Policies to encourage energy efficiency

Chinese government policies for technology innovation address rising energy efficiency standards and subsidies for energy efficient production. Thanks to the implementation of labelling within the efficiency standard system, some low-efficiency electric appliances have been eliminated from the market, and manufacturers have been encouraged to innovate rapidly to adapt to rising efficiency thresholds.

In 2013, sales of high-efficiency air conditioners reached 20% of the market, an 80% increase from 2012. Variable frequency drives or inverters, key contributors to improvements in energy efficiency, developed into a mainstream technology in the air-conditioning market. By mid-2014, this technology had taken 67.2% of the market share and brought down prices. In the middle of 2013, China ended subsidies on air conditioners.

As of 2013, the government had set aside more than USD 4.5 billion for energy-saving projects, saving 12 million tonnes of coal equivalent (Mtce). The projects distributed over 90 million energy-saving electric home appliances, over 3.5 million energy-saving vehicles, over 14 GW of energy efficient electrical machines and 160 million energy-saving lighting products (NDRC, 2013).

Adjusting policy levers

Financing for energy technology innovation comes from state R&D funding, government subsidies, preferential government procurement and venture capital. Since 2012, USD 790 million (CNY 4.9 billion) has been invested from the central government's budget and USD 420 million (CNY 2.6 billion) in fiscal schemes to support 2 411 efficiency technologies, model industries, energy management and monitoring institutions, efficient buildings, and green lighting. Energy savings have totalled more than 20 Mtce (NDRC, 2013).

MOST managed USD 15.2 billion in national S&T programmes during the 11th FYP period (2006-11). More than 60% of the funds were invested in the Basic Research Programme, the National High-Tech R&D Programme and the National S&T Support Programme, with energy technology innovation a key focus. Funding was provided for pilot projects such as those established during the 2010 Shanghai World Expo, where several S&T programmes were deployed in areas including light-emitting diode (LED) lighting, clean energy, smart grids and EVs.

Policy innovation is also being pursued in the context of developing emerging industries, where SMEs are prevalent. Limited by the disadvantage in credit competition with SOEs, SMEs have been suffering from a lack of financing. To help address this gap and encourage SME financing from China's large banks, local governments have developed pilot programmes for technology-based SMEs. These programmes are based on a mix of government and public guarantees and initially have followed three key models:

- **Beijing model:** IP from cash-strapped enterprises is assessed by a law firm, an asset appraisal agency and a loan guarantee company providing credit advisory services and sharing risk together with the bank. After loan approval, the local government may subsidise the interest paid by the SME.
- **Shanghai model:** The value of enterprise IP is assessed by a government-backed intellectual agency advising on credit issued by a bank and further guaranteed by a third-party government-backed funding institution, which shares 95% to 99% of debt risk.
- **Wuhan model:** A hybrid in which the government recommends an enterprise to a bank after the IP is assessed by a third-party agency with both functions — assessment and

loan guarantee. The IP is then institutionally guaranteed to the bank to gain loans, with an additional subsidy provided by the government to the SME to repay the interest after mortgage approval.

In 2012, the yearly financing of IP mortgages reached USD 2.3 billion for patents, USD 3.5 billion for trademarks and USD 0.4 billion for copyrights (Zhonglun Law Firm, 2014), though challenges remain for scaling programmes due to a lack of existing IP protection; the early stage of China's IP asset assessment system; and high costs of IP disposal in a nascent IP market.

A new round of SOE reform

With important roles in the innovation system, SOEs, including those supervised by the central government and those invested in and controlled by local governments, are both the advisers to national innovation strategy and the practitioners investing in innovation capacity. SOE developments and strategies can significantly influence national performance and innovation models, especially when backbone industries, supervised by SASAC and local state-owned assets administrations, serve as the weathervane of policy orientation and potential reform.

Broadly speaking, SOE reform has been ongoing since 1978. With its twin aims of moving China's centralised economy towards a market-oriented economy at the macro level and transforming its SOEs into modern enterprises at the micro level, much progress has been made. The main elements of reform achieved during the 11th FYP included "grasping the large and letting go the small", severing the link between the state and labour, as well as adjusting the state's position towards shareholders (Garnaut, Song and Woo, 2009). The shareholder restructuring which continues into the 12th FYP is seeking to encourage greater market competition and more efficiently link performance with evaluation and incentives for SOE managers. In the past, incentives were not directly tied to commercial performance and hence left gaps, overlapping responsibilities and increased burden by the state in providing additional support for underperforming assets and inadequate services.

Shanghai is at the front line of the new SOE reform. SOE portfolios promote mergers, acquisitions and restructuring among SOEs to get rid of non-essential business. New reforms press SOE shares in public utilities and monopoly industries to open to private investment with mixed ownership encouraged to provide both state and private enterprise guidance. For instance, Petro China announced a mixed ownership reform model in its oil production, pipeline and sales businesses; specifically, the Jilin and Dagang oil fields will offer 35% of ownership to private investment. China's national policy makers are also increasingly interested in allowing room in the energy sector for new market entrants to meet challenges in generation, supply, T&D, and to reform pricing structures in line with market forces. State grid and power sector reforms currently under consideration would unbundle vertically integrated monopolies, and encourage policies that separate generation from T&D assets.

Progress of S&T reform

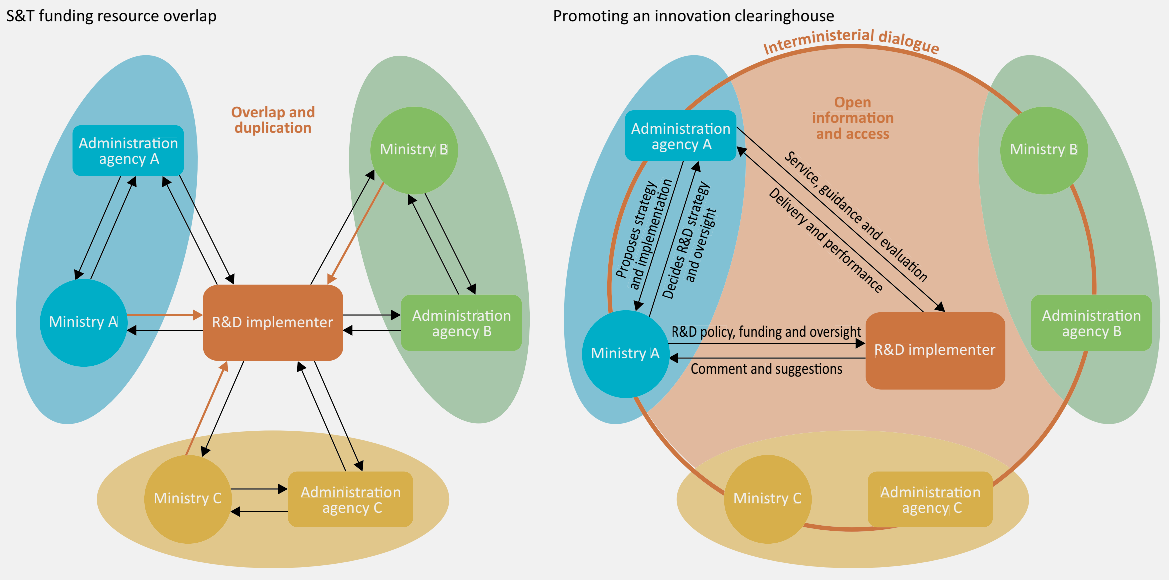
China has demonstrated some progress in its low-carbon and energy sector development. However, the innovation management system, inter-ministerial co-ordination and national-local linkages need improvement. At present, funds for energy S&T are scattered. Projects or programmes managed by different ministries or committees affiliated to the central government have led to fragmentation, low efficiency and overlapping funding. The distribution and supervision of funds have also led to corruption, due to lack of transparent frameworks or effective oversight to streamline functions in fund allocation, monitoring and evaluation of performance.

Promotion of more efficient RD&D resource allocation, especially S&T funding, can benefit both the public and private sectors by offering greater information disclosure and transparency to foster more competitive bidding and evaluation. Generally, public information flow can be beneficial in creating competition and credibility in fund allocation and facilitating international collaboration and communication, by encouraging foreign partnerships and aligning approaches to multinational research efforts.

Meanwhile, streamlined ministerial dialogue to co-ordinate targets from different stakeholders and lower management costs is important in evaluation. The American Recovery and Reinvestment Act, which provided significant innovation and S&T funding, presents a model for enhancing funding efficiency while lowering the management cost by introducing transparent public supervision. It provides public and private stakeholders with easy online access to Recovery Act spending data, including contracts, loans and awards, and tracks the targets, applicant criteria and record of performance in public procurement.

Existing gaps create opportunities for institutional reform to promote innovation, such as an existing concept of developing an innovation ªclearing houseº (Figure 8.12). A clearing house mechanism can track total public funding, options to leverage funding from related programmes, or specific S&T development targets assisted by public-private partnerships. Such a clearing house could provide fund managers with easily identifiable reference points. It can assist in strengthening the centralised strategy formulation and management of third-party or agency implementation, while still enabling competitive, market-driven allocation of R&D and S&T funding.

Figure 8.12 Opportunities for institutional innovation: A technology and innovation clearing house


S&T funding resource overlap

Promoting an innovation clearinghouse

Key point *China has an opportunity to structure its institutional framework to boost innovation capacity, principally by its management of S&T and innovation funds.*

China is currently developing this concept as part of S&T funding reform; it will include fund distribution across five priority programmes and cover management and inter-ministerial consultation issues. In this programme the central government will step back from managing state research funds, thus handing over authority to a third-party agency to develop guidelines based on a state development strategy. Meanwhile, an online system has been established to ensure that S&T reports on progress and achievements from funded projects are available for public review.

At the time of writing, detailed reforms and supporting policies were yet to be released; information transparency to create a more competitive, open system and create the spill-over of knowledge to the public is likely to be significantly promoted and necessary to drive an effective innovation process.

Energy technology innovation: Opportunities and challenges

China's unique approach – or **"innovation with Chinese characteristics"** – is based on implementing market and social reforms aimed at bringing about fundamental technological, organisational and cultural change. China's academic literature, innovation theory and related policy statements promote a concept of "indigenous innovation", with three subcategories or processes:

- **Original innovation** (**原始创新, yuanshi chuangxin**)**:** Independent development and commercial deployment of a technology or device, based on scientific discovery, inventions and principles that have never appeared before, generally in fields of fundamental research and high-tech R&D.
- **Integrated innovation** (**集成创新, jicheng chuangxin**)**:** Selecting and integrating innovative elements and content to formulate new products. Each part of the product is not originally invented, but the end product is an invention with parts of the production chain or adapted technology.
- **Optimised innovation** (引进消化吸收再创新, yinjin xiaohua xishou zai chuangxin): The importation and adoption of technology or joint production, to carry out learning and optimise performance.

These subcategories overlap, forming a comprehensive approach to building indigenous innovation capacity in the Chinese context. For instance, if a product were to contain only one clearly identifiable locally generated patent, it would be considered an "indigenous innovation product" (Ernst, 2010). The combination of private and public sector efforts, especially at the international level, is a key enabler and a key outcome of indigenous innovation. These subcategories broadly mirror the three broad classifications described in Chapter 7 by which emerging economies acquire low-carbon technology, namely, "adopt", "adapt" and "develop".

China's innovation strengths

Clear long-term policy expectations and market signals are vital for innovation in energy technology and systems; they limit risk and give market players greater security in making large investments in R&D and infrastructure. China is increasingly steering away from FYPs; interim action plans have extended this interval to 7 years, or even 15. The Action Plan for Energy Development Strategy (2014–20), for example, provides pricing targets for wind and PV power, supplying the market with a clear signal of subsidy reform.

Its expanding global market share of technologies provides an opportunity for China to lower manufacturing costs and increases the global R&D budget for technology innovation. China's participation in the global renewable energy market has led to lower global prices and reduced overall mitigation costs. This is visible through China's increasing exports of key low-carbon technology and its significant share of global high-tech manufactured goods (Table 8.1). Know-how across aspects of design and process efficiency can have a significant impact on global innovation outcomes (see Chapter 7).

Table 8.1 China high-tech exports and key energy technology exports

USD million	2011	2012	2013
Thermostats	321	407	436
Solar water heaters	124	116	113
LEDs	2 073	2 508	3 473
Wind turbine blades and hubs	533	765	734
Gas turbines < 5 MW	2	3	11
New energy vehicles	34	38	46
Total	**3 087**	**3 838**	**4 813**
Solar cells	22 565	12 788	10 151
China's total export of high-tech R&D	**548 790**	**601 196**	**660 330**
Share of global high-tech exports	**26%**	**26%**	..

Notes: ".." indicates data is not available. USD values are rounded to the nearest million. The decrease in exports of solar cells arose as the result of a trade dispute with the United States, the economic downturn in Europe and the European Union's imposition of provisional anti-dumping duties on imports of solar panels, cells and wafers from China.
Sources: ITC (International Trade Centre) Trade Map (2014), ITC trade map database, www.trademap.org/Index.aspx (accessed 20 January 2015); MOFCOM (Ministry of Commerce of China) (2014), *Statistics of China's import and export of high-tech products*, MOFCOM, Beijing, http://cys.mofcom.gov.cn/article/zt_gxjs/subjectgg/? (accessed 20 January 2015).

Meanwhile, with the large investments in education, human resource and talent development programmes, China is seeking to tap into its "talent diaspora", including overseas students and returning professionals, to contribute to China's knowledge learning and in turn the transfer of know-how. For instance, China's "One Thousand Plan", a national talent and human resource development plan implemented since 2008, claims to have attracted over 4 000 research, management, education and business experts from overseas by providing incentives, project funding and advancement opportunities.

IP governance

Due to a lack of legal enforcement, the issue of protecting intellectual property rights (IPR)[4] has been a major hurdle for most companies to overcome when thinking about entering the China market. As it moves its manufacturing base and technology deployment up the value chain, it is essential that China becomes more respectful of (IPR). Since joining the World Trade Organization (WTO) in 2001, its legal framework has been strengthened and its IPR laws and regulations amended to further comply with the WTO Agreement. Despite this, China continues to draw censure regarding its laxity in protecting IPR.

In seeking to enhance its international image and to improve judicial practice, the first specialised court to handle IP cases was established in Beijing in late 2014. Courts dedicated to handling trials on patents, trademarks and computer software issues were also set up in Shanghai and southern Guangzhou. Furthermore, the Supreme Court has said it will set up an IP protection research centre and train technical investigation officers to help judges who need professional expertise.

IP governance and IP collaboration has also been the focus of deliberations in the Clean Energy Research Center, with discussions taking place between representatives of the United States Department of Energy (US DOE), and China's MOST and NEA. While each side is to fund the research activities of its own scientists, any IPR created under this

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[4] Intellectual property rights are the legal rights protecting the owners of IP.

protocol through cooperative activities is to be owned jointly by both sides as stipulated in cooperative Technology Management Plans (Lewis, 2013).

IP quality and innovation system performance

As well as long-term planning, innovation benefits from a well-functioning IP system (see Chapter 7); however, China's has not been performing well. China's patent law, established in 1984, was the foundation of an IP system covering the whole innovation chain, including R&D and industry and trade development. In 2013, 745 000 patents were filed in China, the highest number in the world. China's State Intellectual Property Office granted 208 000 patents for inventions, 144 000 originating in China. But only 5% of Chinese patents were filed abroad; by contrast, one-third of Japanese patents originally filed in Japan were filed abroad (The Economist, 2014). While the quantity of patents is important, to fully appreciate the value of IP, it is also important to consider commercialisation, licensing and production, patent transfers, their use as capital investment, and the scale of compensations for patent infringement. In relation to these latter categories, China's performance has not been compelling to date.

Generally, an increase in Chinese IP has not translated to innovation competitiveness. Many patents have lain dormant, become obsolete at an early stage or expired after only six years. Many factors contribute to this accumulation of "junk patents". Patent evaluation has been poor. Incentives have focused on quantity over quality, and emphasise IP creation over IP commercialisation. IP enforcement has been inadequate, and a lack of asset assessment systems has inhibited value optimisation through IP transfer or mortgage. Lengthy approval processes reduce IP value, and IP disputes create high costs in China's immature IP protection system. Remedying this situation is vital to build China's innovative and creative capacity.

China's global opportunity: Innovation driven by domestic and global demand

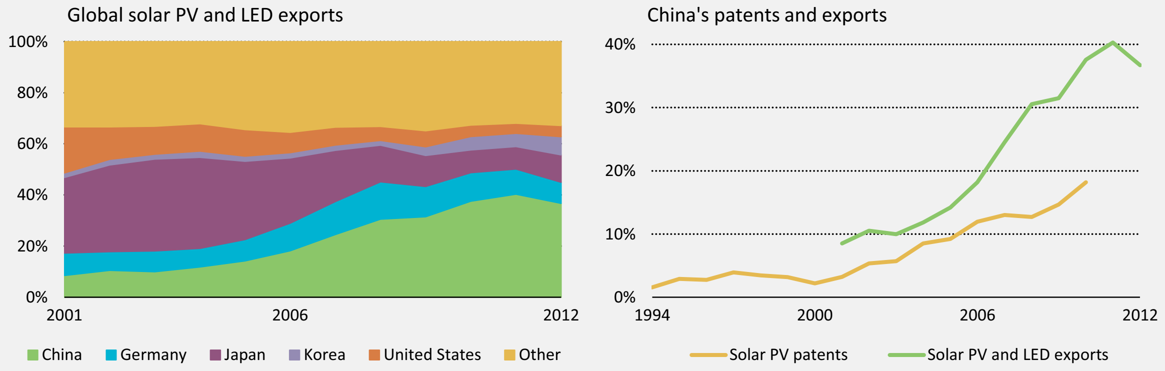
Although the pace of China's economic growth has slowed in recent years, its 7.4% GDP growth rate in 2014 still drives significant energy consumption. Deployment of energy technologies for renewables and cleaner fossil fuels has expanded in China, much as it has in other parts of the world but at a faster and greater scale. China's innovation progress may be illustrated by the increase in its share of global solar power and LED exports, from less than 10% to almost 40% in 2014 (Figure 8.13). Over the same period, this has correlated closely with an increase in patent development.

However, in October 2011, a round of trade battles, starting with complaints filed with the WTO, sparked an investigation. As a result, in 2012, the United States imposed a tariff on solar imports from China. With pressure from these trade disputes, the emphasis on developing the domestic market was increased, generating an opportunity for innovation and accelerated deployment. In solar PV, China's 2015 target for deployment was initially 21 GW of total installed capacity; however, given NEA had estimated 12 GW of installed capacity in 2014 alone, this target was revised upwards to 35 GW by the end of 2015 and advanced again to 70 GW by 2017.

Supportive policies and subsidies, and detailed rules and mandates for grid integration of distributed power, continue to stimulate investment and production. In the pilot free-trade zone in Shanghai, capital-intensive and technology-intensive energy industries will have the opportunity to benefit from international investment and access to global markets.

The recent economic downturn has created opportunities for industry in key sectors such as wind and solar to consolidate, forcing inefficient producers out of the market. As China seeks to increase its global competitiveness, creating a healthy and competitive domestic market in both quality and efficiency of production will expand global partner and supplier opportunities.

Figure 8.13 Solar and LED global market share and solar PV patent data



Global solar PV and LED exports

China's patents and exports

Note: Solar PV and LED data are included jointly in database as harmonisation code (HS) 854140.
Sources: ITC Trade Map (2014), ITC trade map database, www.trademap.org/Index.aspx (accessed 20 January 2015); Helm, S., Q. Tannock and I. Iliev (2014), "Renewable Energy Technology: Evolution and Policy Implications—Evidence from Patent Literature", *Global Challenges Report*, WIPO, Geneva, www.wipo.int/export/sites/www/policy/en/climate_change/pdf/ccmt_report.pdf.

Key point *China's global export share by value of solar and LEDs has grown significantly to roughly 40%, with its share of patents doubling between 2005 and 2010.*

Encouraging the development of public-private partnerships and advancing funding and financing to support innovative approaches to new market and partnership mechanisms will also be crucial to maximise China's innovation opportunities. For example, the use of state funding to encourage venture capital underpins the establishment of the National Fund for Technology Transfer and Commercialisation (NFTTC) (Box 8.6).

Countering domestic resistance to build a healthy innovation system

The process of restructuring and transforming China's industry exposes regional markets to global trade risks. In this context, regional competition for GDP growth has influenced local government policies. Regional protectionism, one manifestation of this competition, is a barrier to integrating regional markets into national markets, and even into global trade. The slow adoption of alternative energy vehicles in China provides a vivid illustration of local protectionism. Market boundaries have included technology barriers and product catalogues or subsidies that favour local automobile manufacturers, even as the central government objected to local protectionism. In Beijing, plug-in hybrids were denied local support because local companies lacked plug-in hybrid production capacity. A recent policy to exempt new energy vehicles from sales tax gives a strong signal of further market opening to foreign players. Supervision and assessment of policy implementation at the regional level is vital, however. The transfer of GDP intensity assessment to the Green GDP index also provides a way to mitigate regional competition. Meanwhile, local government willingness to give up authority to streamline administration will play a critical role in opening regional markets.

China may be losing competitiveness in manufacturing due to the rising costs of labour and other manufacturing processes and materials. This adds an additional window of opportunity to benefit from earlier deployment of new technologies to maximise the near-term cost advantages, which otherwise may be lost to other low-cost manufacturers in the region and beyond.

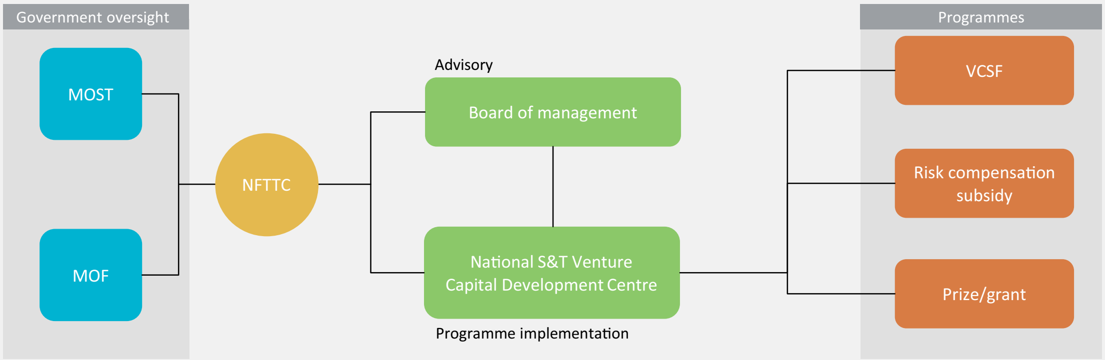
Box 8.6 New model for a venture capital public-private partnership

China's NFTTC was co-established by MOST and the MOF to leverage private sector capital and investment funds to advance commercialisation of innovative technologies, advanced products, materials, equipment and systems promoted by national and regional R&D projects (see Figure 8.14). The general fund is supported by three core programmes including: 1) a venture capital "sub-fund" (VCSF) designed exclusively for venture investment; 2) a risk compensation subsidy of maximum 2% of investment to incentivise bank SME financing; and 3) performance prizes/grants for SMEs.

The VCSF is a public-private partnership platform leveraging private venture capital funds, local government investment, other private equity investment (including foreign capital), and existing government S&T funds. Each individual VCSF aims to raise funds greater than CNY 100 million. The NFTTC contributes 20% to 30% of the total investment and is limited to a minority shareholder. A VCSF is managed by a registered venture capital firm, with a minimum of 0.5% of the VCSF value. VCSF losses are covered first by the venture capital firm and then across shareholders and the public fund.

Initiated in 2014, the VCSF is a nascent programme, Beijing-based venture capital firms have shown strong interest in the programme with six funds in the process of being launched, including from Peking University, Shenzhen Capital Group, Youyou Network and regional government supported science & technology commercialisation programmes.

Figure 8.14 Structure of the NFTTC



Sources: MOST (2011), *Notice on Issuance of Interim Measures for the NFTTC*, MOST, Beijing, www.most.gov.cn/tjcw/tczcwj/201205/t20120517_94467.htm (accessed 20 January 2015); MOST (2014), *Interim Measures for the VCSF of the National Fund for Technology Transfer and Commercialisation Venture Capital Fund*, MOST, Beijing, www.nfttc.gov.cn/html/content/?192 (accessed 20 January 2015).

Key point *The NFTTC is an important government initiative targeted at stimulating financing for innovation and SME commercialisation.*

The convergence of energy and S&T policy

China's long-term energy policy objectives are closely linked to its current energy challenge: to secure a future of safe, reliable, economically efficient and clean energy. Simultaneously, in the near term, S&T policy seeks to increase R&D intensity, enhance innovation capacity, increase links between technology and the economy, benefit social welfare, and foster greater talent and skills. Over the past decade, China has used its energy and S&T policies to advance technology development and deployment.

As a cornerstone of China's innovation drive, the National Outline places energy at the top of its 11 key S&T fields, promoting energy savings, cleaner use of coal, renewable energy and grid security. Advanced energy technologies, such as hydrogen, magnetic confinement fusion and distributed energy are key elements. After release of the National Outline, the five-year state funding of RD&D programmes rose from USD 5.0 billion (2001-05) to USD 8.6 billion (2006-10).

Similarly, S&T plays a central role in energy plans. During the 12th FYP period (2011-15), the energy plan calls for innovation and enhancing high-tech capacity. A specific national plan for the development of energy technology during the 12th FYP, covering key fossil energy technologies and renewable energy breakthroughs, further fostered this innovation focus.

A programme known as National Science and Technology Major Projects, established in the National Outline, seeks to break through critical S&T barriers to meet China's ambitions in obtaining strategic technologies and advanced production such as large aircraft manufacturing and space programmes. Major projects are led by ministries or large SOEs. Since 2006, 16 major projects, including two energy projects – oil and gas field development, and nuclear energy development – have been proposed and implemented (Box 8.7). Though climate change or low-carbon technologies were not directly mentioned as objectives of the two energy-related major projects, the related benefits of these major projects illustrate low-carbon opportunities where energy, S&T and climate change concerns converge.

Box 8.7 National S&T Major Projects focused on energy

Energy development is the core focus of two of the major projects developed under the National Outline. One project aims to advance innovation in China's oil, gas and coalbed methane technologies to boost energy security. This includes reinforcing unconventional oil and gas exploration and enhanced oil recovery (EOR). More than USD 4.5 billion was earmarked by the central government, leveraging over USD 18 billion in investment from relevant enterprises. These funds have facilitated development of projects including shale gas development and CCS. These two options provide potential routes to lower China's emissions profile from fossil fuel combustion. Though still at a nascent phase, projects continue to develop, such as China's first industrial-scale test site operated by PetroChina, an EOR demonstration project with an injection capacity of 100 000 tCO_2/yr, in the Jilin Oilfield (ACCA21, 2013).

The other major project involves large-scale nuclear power with an advanced pressurised water reactor and a high-temperature gas-cooled reactor. It seeks to achieve China's 2020 nuclear power target of 58 GW (lowered again, after it was earlier revised downwards from 80 GW to 70 GW following the Fukushima Daiichi accident in Japan). By the end of 2014, 30 GW of capacity were under construction. The central government has invested over USD 2.4 billion (NEA, 2011). While the Fukushima Daiichi accident has slowed this major S&T project, high-level commitments reinforce the potential for nuclear power to remain an important option for China.

China's SEIs: Innovation at a nexus

The convergence of energy and S&T policies is happening at a time of China's industrial transformation. This can be seen in the specific policy decision to identify seven key SEIs, as highlighted in Table 8.2, as well as transforming traditional industries by eliminating inefficient production capacity. The policies also seek to enhance the development of the service industry, promote cleaner fossil fuels and non-fossil energy technologies, and enhance evaluation, accounting, and energy efficiency standards and labelling, to promote energy-saving technologies, products and overall SEIs. They are tasked with developing a batch of key technologies, enhancing platforms for industry innovation and strengthening technology integration and industrial capacity. The aim is to cultivate market development and innovation-based industrial clusters, by technology demonstration and innovative operations.

Table 8.2 Key developments in strategic emerging industries

Sector	Policy	Technology innovation	Milestone/impact
Energy conservation and environmental protection	With ministerial support, China's semiconductor lighting industry will eliminate incandescent lamps with power lower than 60 watts by 2015, increasing targets for LED lighting to 20% of the total market.	CAS and Sunfor announced a new type of rare earth material to address LED's intermittency and to lower the cost and energy consumption by 20% and 15% compared with traditional LEDs (S&T Daily, 2013).	Annual energy intensity fell by 4.8% in 2014, the largest reduction in four years (NDRC, 2015).
Next generation information technology	83 cities are included in a national smart city pilot programme that addresses information and communication technology (ICT) networks, cloud computing, and big data for city planning, construction and management.	The smart grid network connections of the China Southern Power Grid (CSG) are to be integrated with an ICT system.	In 2013, the energy consumption per unit of telecommunications services was reduced by 2.81% compared to 2012, cutting specific energy consumption by 8.62% since 2010 (MIIT, 2013).
Biotechnology	A feed-in tariff of USD 0.12/kWh of biomass power has been implemented. In some regions, an E10 mandate has been introduced, where 10% bioethanol - produced from grain, cassava, sweet potato or sorghum - is blended with 90% gasoline. Demand for biodiesel, aided by support policies, including taxation schemes, is increasing with a focus on recycling and regional scale.	At the R&D level, the combustion temperature of a biomass boiler has been sustained at 1 000°C and has hit a thermal efficiency of 92%. Advanced research and demonstration into cellulosic and advanced biofuels from macro and micro algae has been encouraged.	China's 2020 biomass power target is 30 GW. The Civil Aviation Administration in 2012 stated China had the potential to produce 12 Mt of aviation biofuel by 2020 (30% of its total jet fuel). In 2014, China was third largest producer of biofuels (after the United States and Brazil).
Advanced equipment manufacturing	Total railway investment in 2015 is targeted to reach USD 120 billion, a level equivalent to that invested in 2014, coupled with central government directives to support development along high-speed rail routes.	A high-speed permanent-magnet synchronous motor (PMSM) traction system was developed by China CSR Corporation and, following successful ground testing, is expected to enter commercial operation in 2016.	The Chinese high-speed rail line network has expanded to over 16 000 km as of February 2014, ranking it first in the world (PeopleCN, 2015), compared with over 9 000 km built or under construction in 2014 across Spain, France, Germany, Italy and Britain combined (The Economist, 2015).
New energy	343 types of permanent-magnet motors from 15 different manufacturers were included in the "China energy savings programme" high efficiency motor promotion catalogue (2nd batch).	Goldwind announced a newly developed direct drive permanent-magnet generator for ultra-low-speed wind, generating power at wind speeds lower than 5.2 metres per second (CREIA, 2014).	China's wind power capacity reached 96 GW in 2014 and generated 153 TWh of electricity, 2.78% of the total (NEA, 2015).
New materials	An energy consumption lower than 100 kWh per kilogramme was introduced as an indicator for initialising new production capacity of crystalline silicon, a material used in the construction of solar cells.	A new method of recycling and re-use of by-products of crystalline silicon production was announced in Chongqing (ChinaIRN, 2013). With this method, the cost of crystalline silicon and volume of waste products are significantly reduced.	From 2011 to 2015, China's new materials industry generated USD 180 billion.
New energy vehicles	China recently cancelled the sales tax on new energy vehicles, including imported EVs.	CAS announced an optimised fuel cell with an energy density of 430 watt hours per kilogramme (PeopleCN, 2014).	In 2014, the sale of new energy vehicles in China reached 74 800, including 45 000 electric vehicles (Lan and Liu, 2015).

Sources: ChinaIRN (China Industry Research Net) (2013), "Investigation on the Breakthrough of Hydrogenation of Silicon Tetrachloride for Polysilicon Production", ChinaIRN, Shenzhen, www.chinairn.com/news/20130415/112228529.html (accessed 20 January 2015); CPN (China Plan Net) (2010), "High-speed railway strategy and China's urbanisation", CPN, Beijing, www.zgghw.org/html/guihualuntan/lilunyanjiu/2010/1019/8502.html (accessed 19 January 2015); CREIA (Chinese Renewable Energy Industries Association) (2014), *2014 China wind power review and outlook*, CREIA, Beijing; The Economist (2015), "High Speed Rail in Europe: Problems down the line", *The Economist*, 10 January, www.economist.com/news/business/21638109-high-speed-networks-are-spreading-fast-face-rising-competition-problems-down-line (accessed 9 March 2015); Lan, C.H. and Y. Liu (2015), "Breakthrough of the new energy vehicle market in Beijing", *Beijing Business Today*, Beijing, www.bbtnews.com.cn/news/2015-02/17000000214427.shtml (accessed 26 February 2015); MIIT (Ministry of Industry and Information Technology of China) (2013), "Obvious reduction of energy consumption per unit of telecommunications service in 2012", MIIT, Beijing, www.miit.gov.cn/n11293472/n11293832/n11293907/n12246780/15398753.html (accessed 9 March 2015); NDRC (National Development and Reform Commission) (2015), "Positively addressing climate change, opening up a new prospect for the low-carbon development", NDRC, Beijing, www.sdpc.gov.cn/xwzx/xwfb/201502/t20150217_665123.html (accessed 26 February 2015); NEA (National Energy Administration) (2015), "Monitoring report on China's wind power industry in 2014", NEA, www.nea.gov.cn/2015-02/12/c_133989991.htm (accessed 26 February 2015); PeopleCN (2015), "Government Work Report 2015 (full text record)", PeopleCN, Beijing, http://lianghui.people.com.cn/2015npc/n/2015/0305/c394298-26642056.html (accessed 9 March 2015); PeopleCN (2014), "Breakthroughs of SOFC technology in China", *S&T Daily*, Beijing, http://scitech.people.com.cn/n/2014/0901/c1057- 25574658.html (accessed 20 January 2015); S&T Daily (2013), "No bulb, allowing transformation, no intermittency – a new type of LED", *S&T Daily*, Beijing, http://digitalpaper.stdaily.com/http_www.kjrb.com/kjrb/html/2013-06/05/content_207165.htm?div=-1 (accessed 19 January 2015).

China's seven SEIs include energy efficient and environmental technologies, next generation information technology, biotechnology, advanced equipment manufacturing, new energy, new materials, and new energy vehicles. Supporting measures have been issued in succession to optimise the industries' development. So far, 26 provinces and cities, including Beijing and Shanghai, have issued plans or guidelines on the development of the SEIs. The SEIs are anticipated to account for 8% of GDP by 2015 and up to 15% of GDP by 2020.

SEI support funds come from a mix of local government and private enterprise as interim measures for administration of special SEI funds focus on mobilising multiple funding channels. Incentives including tax rebates and financial subsidies have been implemented to assist enterprise investment in SEI areas. This approach seeks to reshuffle market players and level the playing field. However, it is still unclear how foreign-invested companies and international players will benefit. Support policies have local content requirements and government procurement criteria, including requirements for indigenous IPRs to cultivate innovation and technology development, which may discriminate against foreign companies unwilling to import IP. Given complex stakeholder impacts, the SEI programme will likely require iterative testing and modification.

Sector cases illustrating "innovation with Chinese characteristics"

As China seeks to build its indigenous innovation capacity, it is engaging in a wide range of technology, manufacturing and research fields. Many of these are interrelated and can spawn new innovations across a range of fields and technology applications. The cases below highlight the current status in key sectors and technology areas where China may be closing the gap, if not leading, by applying "innovation with Chinese characteristics".

Supercomputing is one example of a leading-edge technology that can apply to several fields, especially in the energy sector (such as nuclear power, grid security and grid integration). At the National Supercomputing Center in Tianjin, China has the world's fastest and most energy efficient supercomputer. The Tianjin Supercomputer uses energy efficient graphic processors provided by a California-based company, with innovations by Chinese engineers. This example illustrates clearly the concept of integrated innovation – adapting and improving technologies developed elsewhere to meet Chinese needs.

Renewable energy

During the 11th FYP period, China made significant progress in developing renewable energy technologies (Tables 8.3 and 8.4). With targets to 2020 set in 2007's "Mid- and long-term plan for the development of renewable energy", successes were built upon during the 12th FYP period with policy measures providing incentives for the deployment of renewables and for further investment. Recently China announced that it will seek to meet 20% of primary energy from non-fossil sources by 2030; this target will inform 13th FYP policies.

Progress to date

In 2013, China's power generation from renewable energy technologies increased by 9%, reaching an estimated 1 097 TWh. The share of renewables in the power mix rose to 20%, up slightly from 2012. In 2013, China installed 61 GW of renewables capacity, its highest annual renewables addition to date, 86% higher than in 2012; just over half this capacity came from hydropower (31 GW). In 2014, China's wind installations increased by 19.8 GW, with 96.3 GW connected to the grid. With these new additions, China's wind capacity made up 7% of the global total and generated 153 TWh in 2014 (NEA, 2015).

Table 8.3 Renewable energy targets, policies and support mechanisms

2020 targets (GW)		Examples of key deployment policies	Other support
Hydro	420	**Feed-in tariffs:** These apply to onshore wind, solar PV and biomass.	Offshore Wind Development Plan
Onshore wind	170	**Incentives for small-scale generation:** Grid connection fees are waived and net metering is provided for distributed systems < 6 MW.	12th FYP for national strategic industries
Solar PV	47	**Premium for distribution-grid connected PV:** Solar projects receive CNY 0.42/kWh. Additionally, the scheme allows for excess electricity to be sold to the grid at the price of coal power.	Solar Industry Development Plan
Offshore wind	30	**Grid access and priority dispatch:** Projects approved by government are given priority access to the grid; however, this access may not be applied in practice.	Renewable Energy Law
Biomass	30	**Import duty and value-added tax removal:** This applies to equipment for key technologies, including hydro and wind equipment.	12th FYP for climate change
CSP	3	**Carbon-trading scheme pilots:** These were launched in seven provinces as a first phase in introducing country-wide emissions trading schemes (planned to be launched in 2016).	

Table 8.4 Renewable energy developments and direction

Technology type	Key developments	Next in R&D
Solar energy	In 2010, China accounted for almost 50% of global PV cell production, and is a leader in PV cell manufacturing technology. PV efficiency hit 15% for crystalline silicon components and 8% for non-crystalline silicon components. As of 2013, China accounted for more than 63% of global crystalline silicon cell manufacturing capacity (CPIA, 2014). New technologies and new products continue to emerge.	PV cells with crystalline silicon are targeted to hit efficiencies higher than 20% while maintaining low cost. In 2014, China's PV module manufacturer, Trina Solar, at its State Key Laboratory of PV Science and Technology, achieved new efficiency records for p-type and n-type crystalline silicon solar cells with an efficiency of 21.40% for a cell measuring 156 by 156 mm. Results were confirmed by Germany's Fraunhofer ISE CalLab. +20% efficiency targets have also been confirmed by researchers at the Japan Electrical Safety & Environment Technical Laboratories (JET) and at the Australian National University (ANU). Apart from solar PV, solar thermal energy is also actively being pursued in China.
Wind power	By the end of 2014, China's total installed capacity of wind power reached 153 GW. Domestic manufacturers have developed technology for producing the main components of wind power equipment of capacity higher than 1.5 MW. In 2013, China surpassed the United States in installed wind power capacity.	Efforts are dedicated to wind power systems of 6 MW to 10 MW for onshore and offshore use. In 2014, a direct drive permanent-magnet generator for ultra-low wind speeds (below 5.2 metres per second) was successfully integrated to the grid.
Biomass technologies	Under the 12th FYP, advanced ethanol (i.e. cellulosic ethanol) is currently receiving the largest subsidy rate at CNY 1 400/tonne as of 2012, while ethanol from food-based feedstocks receives CNY 500/tonne and ethanol from non-edible food-based feedstocks (such as non-edible cassava) receives CNY 70/tonne. China also has an overall biofuels mandate, which calls for 10% biofuels by 2020. Key priorities include industrial-scale biodiesel production; advanced biofuel technologies; biomass and waste-to-gas; co-utilisation technologies and co-firing systems; advanced cogeneration* systems.	Enzymatic research and cellulosic ethanol are key areas where funding has been increased and will likely continue. International partnerships have also included joint research on advanced biofuels for aviation, including the use of algae-based feedstock.

* Cogeneration is synonymous with combined heat and power (CHP).

In 2014, China installed 12 GW of solar PV capacity, which was the world's largest annual growth of the technology to date (IEA, 2014b). High project costs and technical challenges remain significant barriers to deployment, however. China also added an estimated 500 MW of bioenergy and 25 MW from CSP plants. Bioenergy is expected to expand by between 2 GW and 4 GW per year, in line with FYP targets, though the establishment of sustainable feedstock supply and local opposition to waste-to-energy plants are constraints. Waste-to-energy plants are likely to play an important role in development, given limited landfill space in many Chinese cities. Other technologies, such as CSP and offshore wind, face high costs and technology challenges that may be overcome with innovation and technology improvement.

In 2013, 90% of newly installed wind capacity was connected to the grid, up from 80% in 2012. Although grid-connected projects dominated PV deployment in 2013, the NEA's plans for 2014 included 8 GW of distributed generation projects and only 6 GW of utility-scale installations. Access to attractive financing and incentives to make distributed solar PV projects bankable are needed to meet deployment targets. The economic attractiveness of less mature technologies, such as CSP and offshore wind, remains uncertain. Both CSP and offshore wind require higher incentives than solar PV and onshore wind. CSP system costs remain high, with low levels of commercialisation. Further development of CSP, whether hybrid designs with coal or pure solar, could provide a positive mechanism for providing storage and flexibility.

China's target is to install 1 GW of CSP capacity, with a thermal collection area of 3 GW, by the end of 2015. In the national energy S&T plan (2011-15), parabolic trough designs and tower designs were prioritised with construction of 300 MW CSP plants integrated with coal-fired power generation, 50 MW CSP with parabolic trough design, and 100 MW solar thermal plants with parallel installed towers. In 2011, China installed a heliostat tower CSP plant of 1.5 MW, supplying 1.95 gigawatt hours of electricity per year after connecting to the grid. The first commercial 10 MW to 50 MW tower commissioned in China was built by SUPCON at Delingha in Qinghai Province (CSPPLAZA, 2014).

As one of the potential backbones of the energy mix in China, the further large-scale dissemination of renewables relies heavily on the extent to which the barriers of integration with the grid and electricity markets through market-led approaches can be overcome. S&T, aiming at lowering costs, will continue to play the role of a catalyst in the deployment and diffusion process (Table 8.5).

Table 8.5

Key challenges and actions in S&T systems and innovation in renewables in China

Challenge	Path forward
Grid integration and upgrades	**Addressing financial and non-financial barriers**
▪ Large-scale and fast deployment need to be matched by effective grid integration and market structures. ▪ T&D infrastructure and large-scale planning require long lead times, and policy and structural reform.	▪ Design effective allocation to fund advanced R&D. ▪ Develop successful pipeline of projects and markets to incentivise grid development and distribution. ▪ Promote effective management and interplay of incentives policies.
Market and policy reform	**Accelerate technology innovation through international collaboration and competition**
▪ Balancing demand with market pricing reform and regional power market integration to support micro-grid and systems integration is critical. ▪ Ensure ample availability and low-cost financing.	▪ Expand networks and co-operation in technical exchanges and policy forums. ▪ Develop South-South partnerships to support technology transfer and diffusion of advanced renewable technologies.

Electric vehicles

With over 137 million vehicles on the road (NBS, 2014b) and passenger vehicles sales growing at over 15% per year (CAAM, 2014a), China faces growing concerns over energy security and urban air pollution. To reduce fuel use and emissions from transportation, the government has allocated funding to support new energy vehicles.[5] Alternative fuels, such as natural gas or propane, for heavy fleet vehicles have also been a focus of co-operation between China and the United States. While plans include ambitious EV-specific targets (including cumulative production/sales of 500 000 EVs by 2015 and 5 million by 2020), the government also seeks to facilitate competition among vehicle technologies via technology-neutral fuel economy standards[6] and R&D support for alternative technologies and fuels (e.g. fuel cell vehicles [FCVs]).

Since the 1990s, the government has supported R&D in EV technology and other alternative fuel vehicles.[7] In 2010, the government formed the SOE Electric Vehicle Industry Alliance (SEVIA) to support indigenous innovation, bringing together SOEs in the automotive industry, battery industry, charging services and real estate sectors to collaborate on EV R&D, standards, and IP sharing. The new energy vehicle industry is one of China's seven key SEIs.

The government has sought to increase market demand for EVs through demonstration and incentive programmes. The Ten Cities, One Thousand Vehicles programme was launched in 2009 to demonstrate and deploy EVs, growing to 25 cities by 2011. Purchase subsidies for consumers began in 2010, with an initial two-year pilot project in five cities (Hao et al., 2014). Some cities offered additional incentives, including matching subsidies (though restricted to locally produced vehicles), free license plates, exemption from vehicle use restrictions and preferential parking. A second phase of incentives runs from 2013-15, expanding to 28 cities and regions, prioritising regions with severe air pollution issues. However, even with these generous subsidies, costs remain out of reach for most Chinese car buyers. The slow deployment of public chargers and the barriers to home charging have also hindered deployment.

Progress to date

Based on key indicators of R&D funding – scientific publications and patent applications – the results of EV innovation policies have been mixed. Peer-reviewed publications by Chinese scientists related to EVs, particularly battery technology, have increased significantly in recent years. Patent filings, which demonstrate the commercial application of research, have been robust domestically, but limited internationally. China holds only 3.4% of transnational lithium ion battery patents, compared with 52% for Japan and 21% for the United States (JPO, 2010). The disparity may be partly explained by the more immediate focus on China's large domestic EV market, which may influence the motivation of domestic manufacturers to explore other markets.

Auto manufacturers in China produced and sold over 17 500 EVs in 2013, up 38% from 2012 (CAAM, 2014b) but still well below the targets set. This represents only around 0.1% of total vehicle sales, the majority as government procurement. The Ten Cities, One Thousand Vehicles programme included a successful pilot in Shenzhen, Guangdong province, where creative leasing and subsidy schemes, developed through partnerships between government and financial, energy, public transportation and taxi companies, facilitated deployment of

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[5] New energy vehicles include hybrid electric, plug-in hybrid electric (PHEV), battery electric, FCV and other alternative fuel vehicles (e.g. fuelled by compressed natural gas and biofuels).

[6] 6.9 litres gasoline equivalent per 100 kilometres (lge/100 km) by 2015 and 5.0 lge/100 km by 2020, which surpass US standards over this period.

[7] For example: 2004 Policy on the Development of the Automotive Industry; 2006 "863 Programme" on Energy Saving and New Energy Vehicles Project; and 2009 Automotive Readjustment and Revitalisation Plan.

2 050 electric buses and an all-electric taxi fleet of 300 vehicles (Ma, 2013). This has helped to develop a strong EV industry in Shenzhen, led by a local vehicle manufacturer, BYD. That said, BYD's success beyond Guangdong has been hampered until recently by "local only" restrictions on subsidies; these rules were lifted in 2014 and sales of the BYD "Qin" PHEV have since grown in Beijing and Shanghai. In 2014, fast charging stations were constructed at 50 km intervals along the 1 262 km Beijing-Shanghai highway. Additionally, the NEA is planning the construction of 4.5 million EV charging stations by 2020.

Challenges and path forward

China's EV market will continue to grow and is expected to become the largest in the world by 2020 (Tagscherer and Frietsch, 2014). Meeting domestic EV demand alone could create 20 000 direct vehicle manufacturing jobs (Deutsche Bank Group, 2012), in addition to those in the component supply chain. Growth in EVs will support other SEIs, notably renewable energy and new materials. For instance, EVs can facilitate increased renewables deployment and integration, particularly wind, through "smart" overnight charging. There are also opportunities to build on the success of electric two-wheelers and PHEV buses. Actions proposed to further develop the EV market can maximise the associated economic and environmental benefits (Table 8.6).

Table 8.6 Key challenges and actions to develop the Chinese EV market

Challenge	Path forward
Lagging R&D and IP development	**Consider international innovation networks and opportunities to integrate**
▪ Limited domestic capacity to develop world-class EV technology. ▪ Pursuit of original and local innovation objectives may conflict with opportunities to meet targets domestically and abroad. ▪ Local protectionism has distorted the market, hindering competition and innovation. ▪ Fast-paced traditional auto industry development creates competition for R&D and incentives for EVs.	▪ Collaborate with international auto makers to accelerate domestic IP development, to follow success of high-speed rail and wind turbine industries. ▪ Consider innovative approaches to increase competition, such as the decentralised "open modular" approach used in the electric two-wheeler industry (Weinert, Ma and Cherry, 2007).* ▪ Continue to address local protectionism at the federal level (Wan, Sperling and Wang, 2015).
Low consumer adoption to date	**Address financial and non-financial barriers**
▪ Even with subsidies, costs remain out of reach for most car buyers. ▪ Slow deployment of public chargers and limited home recharge potential in dominant apartment and urban dwellings. ▪ Inexperience and low consumer confidence in alternative vehicle technologies.	▪ Develop models for the lower end market (i.e. market segmentation). ▪ Deploy public charging stations. ▪ Consider innovative policy, e.g. exempt EVs from congestion charges, license plate registration queues and fees, and purchase taxes; place restrictions on conventional vehicles in city centres.** ▪ Develop international partnerships and suppliers.
Upstream environmental impacts of electricity	**Optimise deployment system: implement systemic, complementary policies**
▪ Environmental benefits are limited without complementary electricity policy, given China's reliance on coal-fired generation.	▪ Prioritise EV adoption in "low-emission zones" to drive widespread adoption. ▪ Implement clean electricity technologies and policy, e.g. renewables and smart charging.

* In an "open-modular" industry, such as the electric two-wheeler industry in China, manufacturers act as assemblers and source "modular" components from a decentralised network of suppliers, which can lead to increased competition and lower costs. This contrasts with traditional auto manufacturing, where assemblers typically work with a few key "trusted" suppliers. Adopting an "open modular" structure would require strong standardisation and functionally independent components, and may face specific challenges in a more complex technology such as that in EVs.

** The rapid adoption of electric two-wheelers was driven largely by a ban on gas motorcycles within city limits; phasing in a similar policy for gasoline vehicles may be controversial but effective in accelerating EV adoption in cities with poor air quality.

CCS

CCS[8] is highlighted in China's national short- and long-term plans for addressing climate change. After being mentioned in the National Outline as a key approach to near-zero emissions, the development of CCS was emphasised in many national working plans dealing with GHG control, energy conservation and environmental protection. During the 11th and 12th FYPs, the government significantly increased investment in CCS technology RD&D.

Efforts to support national investment have ranged from technical studies and pilot projects to supporting industrial-scale demonstrations and the assessment of potential CO_2 storage sites. In the most recent special national plan for CCS, research was directed towards CO_2 capture technology, CO_2 storage site identification, and CO_2 leakage risk assessment and management. Plans for demonstration are mainly targeted at the power, iron and steel, cement, and chemicals sectors, with EOR and chemicals production as the main prospects for CO_2 utilisation. Much of this work is being accomplished in collaboration with international partners, from governments to a range of global companies and equipment providers.

An innovative concept being developed in the context of US-China bilateral agreements on technology co-operation is the development of CO_2 injection to enhance underground water recovery. This concept would focus on applications in coal development zones to recover otherwise inaccessible underground water for use in industrial and cooling processes in drought prone regions. While there is little existing experience in this field, there is interest in developing joint research efforts to overcome some of the technical and economic issues that limit demonstration of this concept, including the methods of injection, identifying suitable saline formations, and addressing the costs relating to the required water treatment and distribution systems.

Progress to date

Major national S&T projects address wide areas of CCS research, from applications in the power sector and industry to the storage behaviour and utilisation of CO_2 in various processes. During the 11th FYP, China engaged in over 20 CCS technology R&D projects, directly investing USD 32 million and driving corporate and state-owned investment of over USD 160 million (CNY 1 billion). In the 12th FYP, China's R&D efforts increased, with more than USD 65 million in public funding being allocated to date (Table 8.7) (ACCA21, 2013).

The government is encouraging and supporting SOEs and other corporate players to engage in large-scale CCS demonstration. EOR was essential to the large-scale demonstration projects established in Shandong and Jilin, both direct outcomes of R&D undertaken by two SOEs, Sinopec and PetroChina. International collaboration has also been effective in advancing CCS. The US-China Clean Energy Research Centre and other bilateral partnerships have advanced knowledge-sharing and joint initiatives in related fields. Australia, Italy and the United Kingdom, among others, have also engaged or are still engaged in collaborative CCS initiatives with China (Table 8.8).

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[8] Chinese authorities often refer to CCS as carbon capture, utilisation and storage (CCUS) to explicitly acknowledge the role of CO_2 utilisation as an alternative to or as a route to CO_2 storage.

Table 8.7 Key CCS innovations at pilot and research scales in China

Project	Technology and key innovation	Capacity (ktCO$_2$/yr)		Status
		Capture	Storage	
CO$_2$ capture project at Shanghai Shingdonkou Power Plant, China Huaneng Group.	China's largest scale pilot for post combustion capture on a coal-fired power plant.	120		Commissioned in 2010
CCS at coal liquefaction plant, China Shenhua Group.	Coal liquefaction and Saline aquifer injection.	100	100	Commissioned in 2011
CO$_2$ capture and utilisation in Jilin oil field, PetroChina.	CO$_2$ from natural gas processing combined with EOR for storage.		100	Commissioned in 2011
Oxyfuel combustion and CO$_2$ capture, Huazhong University of Science and Technology.	China's only Oxyfuel demonstration and one of few globally.	50-100		Commissioned in 2011
CO$_2$ capture with algae-based biodiesel production, ENN Group.	Combining industrial CO$_2$ capture with applications in biofuels production.	20		Early pilot phase
US-China joint research into CO$_2$ for enhanced water recovery.	CO$_2$ captured from coal-fired power generation or other sources is injected into saline aquifers for enhanced water recovery, water treatment, and storage. The treated water may be used as power plant cooling, agricultural water, oil field make-up water, and other industrial and residential uses.			Concept and area of joint research in US-China CCS co-operation with research pioneered by the US National Energy Technology Laboratory (NETL) and others

Note: This is not a comprehensive listing of projects.

Sources: ACCA21 (2013), *Carbon Capture Utilization and Storage Technology Development in China*, MOST (Ministry of Science and Technology)/ACCA21, Beijing; US DOE, National Energy Technology Laboratory, Integrated Carbon Capture and Storage and Extracted Water Treatment, www.netl.doe.gov.

Table 8.8 China's international co-operation initiatives on CCS

Project	Cooperating Institutions	Duration
China-UK NZEC Co-operation (Phase 1)	United Kingdom	2007-09
China-EU Carbon Capture and Storage Co-operation (COACH)	European Union	2007-09
China-US Clean Energy Research Center	MOST, NEA, US Department of Energy	2009-
Sino-Italy CCS Technology Co-operation Project (SICCS)	Enel	2010-12
MOST-IEA co-operation on CCS	IEA	2010-
China-Australia Geological Storage of CO$_2$ (CAGS)	Australian Department of Resources, Energy and Tourism, Geoscience Australia	2012-
Carbon Sequestration Leadership Forum (CSLF) Capacity Building Projects	CSLF member countries	2012-

Notes: This is not a comprehensive listing of projects. No end-year denotes ongoing project.

Challenges and path forward

Altogether 12 large-scale CCS projects are at some stage of development in China (Global CCS Institute, 2014). If they were all realised by 2020, they would enable the capture of around 15 MtCO$_2$/yr, some 50 times the current capacity operating in China.

In developing CCS, China is confronted with many of the challenges facing other nations, e.g. reducing capture costs, developing a business case, investigating storage opportunities and seeking wider acceptance for the technology. While impressive progress has been made in R&D and demonstration, broad deployment of the technology will require the adoption of appropriate policies, regulation and drivers. Policy and industry engagement along with further technology development will be essential to reduce costs and address associated gaps in regulatory, storage availability and pipeline infrastructure. The main challenges facing the development and deployment of CCS in China are summarised in Table 8.9.

Table 8.9 Key challenges and actions to develop CCS in China

Challenge	Path forward
To develop an attractive business case	**Develop the business case for CCS deployment**
▪ high capital investment in the construction of CCS systems ▪ limited demand and potential for large-scale use of captured CO_2 in industry sectors.	▪ reduce costs through the value chain, e.g. by enhancing capture efficiency ▪ explore new applications for captured CO_2, e.g. in large capacity coalbed gas extraction ▪ establish policy drivers relevant for CCS, such as carbon pricing mechanisms.
Risks associated with large and commercial-scale operation	**Accelerate technological innovation and cross-industry collaboration**
▪ limited experience of large-scale application across power and industry sectors ▪ ensuring permanence of CO_2 storage and avoidance of environmental impact.	▪ enhance R&D efforts on the compatibility of capture, transportation, storage and usage technology in key sectors ▪ strengthen collaboration with international partners and cross-industry partners ▪ reinforce R&D and deployment of CO_2 monitoring technology.

A key policy innovation: An energy sector transformed by a market-led command economy?

Since October 2013, China has increased its near-term focus on mobilising market forces and liberalising policies to drive further change in the energy sector. This has included broad structural changes to the market, oversight of SOEs and the opening of opportunities to allow new entrants into previously monopolised markets.

In most sectors crucial to energy and climate challenges, however, command-control measures still dominate. In the coal sector, for example, there has been a focus on consolidation, boosting efficiency, limiting pollutants, reducing environmental impacts and reforming pricing policies, including water consumption and water pricing policies. Ambitious large-scale initiatives, such as high-speed rail and other large industry projects, are also supported by command-control and single purchaser programmes that play an outsized role in how technology demand develops. The development of new innovative sectors and lower carbon energy technologies may depend on China striking a balance between central planning and market forces, as the example on the shale gas industry shows (Box 8.8).

Box 8.8

Shale gas: An innovation opportunity

China's shale gas development may provide significant lessons for market and energy systems reform. It is a new and emerging area where China's technical capabilities lag those of global leaders, but offers a significant opportunity for reducing emissions across China's energy mix.

The nascent sector needs to overcome critical challenges including technology gaps and lack of existing operational expertise and knowledge across several key areas. For instance, China's shale gas reservoir geology and surface conditions pose a more difficult proposition than those of North America, so American technology and experience will need to be improved and adapted for application to Chinese conditions. As the industry emerges, the investment environment and policies need further clarity and transparency to enable domestic and international companies to engage effectively in shale gas exploration and development.

As China seeks to advance its technology innovation in this area, working and co-operating with international players will be crucial, especially with those in North America who lead the market. The form that co-operation will take is still unclear, but early bids and allocation of resource blocks in China demonstrate new opportunities for partnerships.

China's shale gas output in 2015 is expected to reach or even exceed 6.5 bcm, consistent with the national target. A critical issue for further development and innovation is policy and regulatory classification of shale gas to enable smaller entrants into the bidding process and to encourage foreign players and new industry entrants, beyond China's major companies and SOEs.

The list of Chinese companies involved and successful in the bidding process includes not just national oil companies but also non-traditional oil and gas players, producers of chemicals, equipment manufacturers and utilities that are seeking opportunities in this emerging field.

Overview of China's pricing reform policies

Increasingly, China is seeking to implement less interventionist price-setting and price manipulation, and scale back fuel subsidies and conventional pricing of specific commodities to enable more market-led adjustment. The government and more specifically, relevant agencies of the NDRC are pushing ahead with pricing reforms of water, oil, natural gas, electricity, transportation, telecommunications and some other sectors, while relaxing price control in some key competitive areas. As these reforms move forward, government price-setting will be limited to important public utilities, public welfare services and network-based natural monopolies, while increasing transparency and openness of public supervision. China is also seeking to improve the pricing mechanism for agricultural products and attach greater importance to the market's role in determining prices.

In addition, China aims to reform the taxation system, gradually increasing proportions of direct tax and reforming value-added taxes with simplified tax rates. This will include adjusting collection processes and procedures, consumption tax rates, and imposing taxes on inefficient and polluting products along with some high-end consumer goods.

In the power sector, the approach to pricing reforms is critical, as electricity pricing is closely linked to decision making on managing existing assets, new generation mix and managing dispatch, new generation siting, transmission, and distribution. The shape of the reforms will impact the build-out of China's infrastructure over the midterm and to 2050. While it is still unclear what mode the reforms will take and how effectively they will be implemented, the reform process will be guided by nationally determined targets and long-term planning, such as China's medium- to long-term plan to 2020 and the recent 2030 emissions targets.

While solicitations for opinions on power sector reform have been submitted to NDRC for consideration, senior NDRC officials have indicated the central government's interest in two main priorities. The first is to separate China's power T&D businesses and to encourage more private capital to invest in the power generation and distribution sector.

The second priority is to restructure the revenue model of state-owned grid operators, based on a transition from earnings generated from fluctuations in retail tariffs to considering a fixed power transmission fee.

China's future grid: A smarter system to balance the load

Inevitably China will seek a way to establish a stronger, more reliable grid with the system flexibility to integrate large renewable deployment along with large-scale base-load generation. For this, the need to unbundle generation and T&D assets is clear. To continue with the existing structure, which includes the largest global utility, the State Grid Corporation of China (SGCC), as well as other large grid operators across China, would entail designing systems that continue to operate reliably, while also integrating new and competing generation assets and grid infrastructure build-out. Amid the fast-paced deployment of renewables, the difficulty in matching load centres to wind and solar, for example, has proven costly, with significant wind capacity left unconnected to the grid. However, in this case, China has continued to improve grid connections as more capacity comes online. More generally, it will remain a challenge to develop a market-oriented pricing framework that motivates the desire to adopt electricity from various generation sources, while reflecting regional priorities in developing sources adapted to local circumstances.

Technological advances in ultra-high-voltage direct current (UHVDC) transmission suggest it may be a crucial element of China's smarter and more efficient power system, by connecting distant supply and demand centres through key corridors. The scale of development in China's smart grid implementation, amid major structural reforms and infrastructure additions, is likely to make China a significant consumer and developer of smart grid technologies such as UHVDC and distributed generation. With China's energy resources far from demand centres along the coastal rim, construction of China's smart grid will create opportunities for "intelligent" power equipment, meters, appliances and integrated demand-side management systems. China is also developing a UHVDC manufacturing base, challenging established global players.

In August 2013, construction began on a west-to-east UHVDC transmission project to transport about 40 TWh per year from the Xiluodu hydropower plant in southwest China 1 700 km to the eastern province of Zhejiang from 2014. Companies such as XD Group, C-EPRI and NR Electric are increasingly providing UHVDC equipment (Asian Power, 2014).

As the power reforms take shape, China's UHVDC build-out is likely to follow national standards enforced through the state-owned power grid companies, SGCC and CSG. As SGCC has initiated a USD 250 billion upgrade plan, linking regional grids via 20 UHVDC power corridors by 2020, it seeks to address China's geographical energy imbalance, but will also likely strengthen SGCC's stake in China's transmission system. While strong interconnection would allow flexibility, there are concerns that China's regional grids are too weak to receive the large amounts of power transmitted via UHVDC lines, emphasising the need to plan new distributed generation with these linkages in mind.

State-owned companies dominate power generation and SGCC acts as a transmission system operator facilitating offtake of electricity in most of the country, with CSG providing a similar regional role. SGCC resells the power to regional supply monopolies that serve end users at regulated prices, leading to network losses and inefficient dispatch. For Chinese provinces with surplus power, in theory, returns are higher if the electricity can be exported to areas of tighter supply. However, at present, in the absence of a wholesale pricing and market-based dispatch system, NDRC essentially determines the transmission price and the on-grid price of electricity from power plants.

Given the centralised mandate to regulate electricity and fuel prices, significant opportunity exists to bring in greater efficiency and market competition. One approach, based on pricing reform in Shenzhen, allows for market-driven pricing for the generation and sale of electricity by introducing a transmission service fee. Such reforms may have a positive impact on the ability to deploy low-carbon technologies at scale across China. As carbon pricing is further introduced and emissions trading systems deployed, policy interactions with the design of an electricity wholesale market must be further considered. In the Chinese context, wholesale competition and transmission access may prove to deliver a substantial social benefit.

Pricing externalities to drive innovation

By 2012, the end of the Kyoto Protocol's first commitment period, China had built the most extensive Clean Development Mechanism (CDM) programme in the world, specifically encouraging renewable energy and energy efficiency measures. In 2010, China became the leading country based on registered CDM projects (751 projects, 36.4% of the world total), the volume of annual expected certified emission reduction units (205 million tonnes of CO_2-equivalent, or 59.4% of the total), and actual certified emissions reductions issued (186 Mtce, or 48%) (Duan, Pang and Zhang, 2014). Building from this carbon finance experience and other environmental market developments, China has embarked on an ambitious national carbon market pilot system with the aim of building a national carbon emissions system by 2017. As China further develops its energy market reforms and S&T advancement policies, further consideration to linking deployment of carbon markets or other carbon pricing regimes will continue to be a factor in transitioning to cleaner energy technologies.

Initially, NDRC established pilot CO_2 emissions trading schemes in seven regions – Beijing, Chongqing, Guangdong province, Hubei Province, Shanghai, Shenzhen and Tianjin – demonstrating a strong interest in developing a market-based approach to controlling GHG emissions. The pilot systems aim to cover one-third to two-thirds of each jurisdiction's CO_2 emissions, placing caps on emissions intensity, rather than absolute emissions, and allocating all emissions allowances for free, based on different benchmarks of past emissions. While the pilot schemes involve trading only in CO_2 emissions, the Shenzhen scheme also monitors and audits six other types of greenhouse gases. All pilots cover industrial sectors, with some extending coverage of the commercial sector and other institutions.

Together with the pilots, China has established a system of "reporting enterprises" to oversee monitoring, auditing and reporting of emissions for companies outside the mandatory emission control systems. Reporting enterprises are to be gradually included in the carbon trading system. In Guangdong province, companies that emitted 10 000 tCO_2 or had an energy consumption of 5 000 tce per year between 2011 and 2014 were defined as reporting enterprises. By mid-2013, more than 400 enterprises were involved in the trading pilot in Beijing and more than 600 in Shenzhen. A snapshot of emissions allowance pricing in May 2014 shows that prices have been generally comparable with those in other emissions trading systems, such as those in the European Union, California and the United States' Regional Greenhouse Gas Initiative (IEA, 2014a).

Serving as the test bed for a national market that may be developed by 2020, the pilots represented a trading volume of 13.75 $MtCO_2$ and a turnover of more than USD 8 billion by the end of October 2014. In total, 15.21 $MtCO_2$ have been sold at auction (NDRC, 2014).

Recommended actions for the near term

While meeting challenges where innovation, energy and climate change mitigation intersect, there is an opportunity to strengthen and expand China's economy by improving industrial efficiency and supporting technology transformation, not only domestically, but also globally.

As China continues to balance the short-term priorities and real environmental challenges facing its large urban populations with the long-term impacts of today's infrastructure choices, policy developments and institutional processes should seek to harness the co-benefits provided by low-carbon technologies and more resilient innovation and energy systems.

Understanding the environmental impact and market interactions of major supply- and demand-side management technologies may lead to more effective balancing of central planning with market reform measures. SOE reforms relating to power generation should seek to encourage new entrants and the efficient deployment of clean energy technologies, and grid integration across geographies and key sectors.

Monitoring and evaluating innovation measures against energy sector and environmental benefits can help to improve policy implementation over time and lead to more effective innovation systems designed to meet the main public objectives.

Encouraging more domestic demand for technologies can lead to lower-cost global market opportunities. Further engagement with global innovation networks while building domestic institutions can lead to win-win outcomes. Strengthening domestic laws governing enforcement of IP regulations would lead to opportunities and system rewards for innovators and industry leaders. It would also foster greater collaboration with international public and private entities, and more effective public-private partnerships.

In China, IP and research guidance need strengthening to increase the quality of research, improve the value of patent applications and produce a more effective and transparent funding system for innovation.

Improving standard setting and adherence to compliance frameworks and quality assurance may also contribute to fostering global interest and high-value research collaborations.

Policies should be encouraged that guide S&T rather than being prescriptive, i.e. China must avoid "picking winners". Greater competition in procurement and public bidding must be fostered, while setting benchmarks to track performance and avert technology lock-in.

Within SEIs, public procurement and catalogues for important efficiency products and technologies should focus policy incentives on emerging rather than existing technologies to drive innovation, while still supporting the healthy development of nascent industries. To forestall the risk of being or becoming outdated, such catalogues or criteria for incentives should be periodically adjusted to promote advanced technologies.

Chinese energy policy should encourage greater competition and unbundling of generation assets, offtake and T&D services to enable greater flexibility for negotiating contracts between providers and consumers. These actions would facilitate wider deployment of clean energy and smart grid systems. Electricity and energy market reforms should be considered in tandem with wide scale deployment of carbon markets or other carbon pricing regimes.

Chinese policy makers and enterprise leaders can have an important impact on global energy savings, climate mitigation and low-carbon goals. Ambitious efforts in meeting long-term climate targets at an accelerated pace can bring first-mover advantages in a globally competitive innovation environment.

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Annexes

Analytical Approach

Energy Technology Perspectives 2015 (*ETP 2015*) 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 2015* 2°C Scenario (2DS) does not depend on the appearance of breakthrough technologies. All technology options introduced in *ETP 2015* 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 acknowledges those policies that are already implemented or committed. 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.

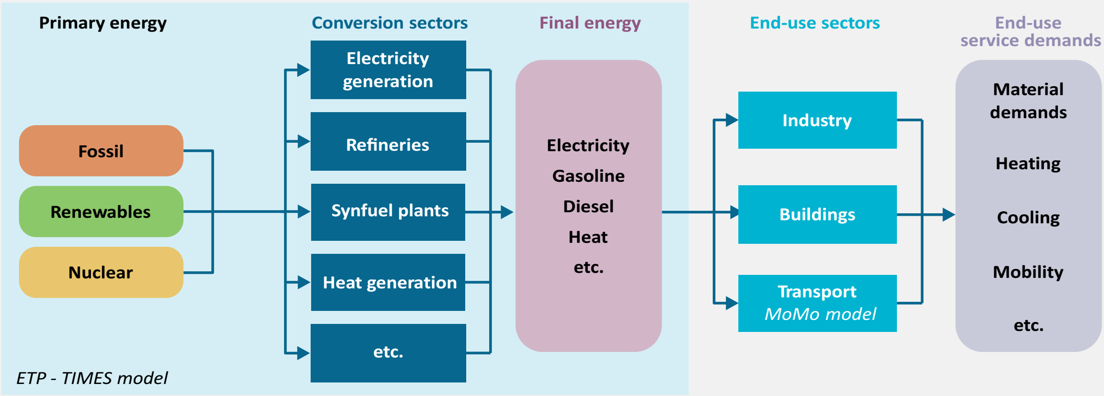
ETP model combines analysis of energy supply and demand

The ETP model, which is the primary analytical tool used in *ETP 2015*, 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-TIMES model



Note: TIMES = The Integrated MARKAL-EFOM System; MoMo = Mobility Model.

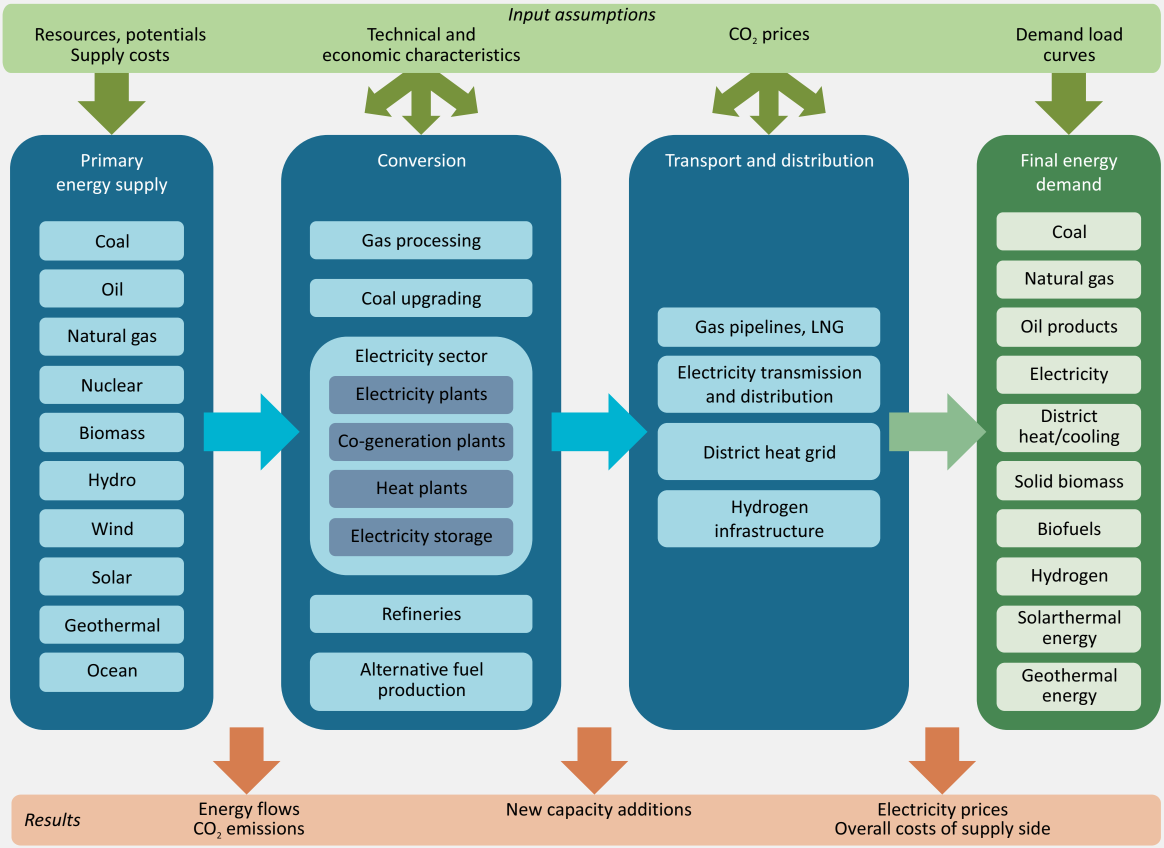
Key point *The ETP model enables a technology-rich, bottom-up analysis of the global energy system.*

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 has been 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.*

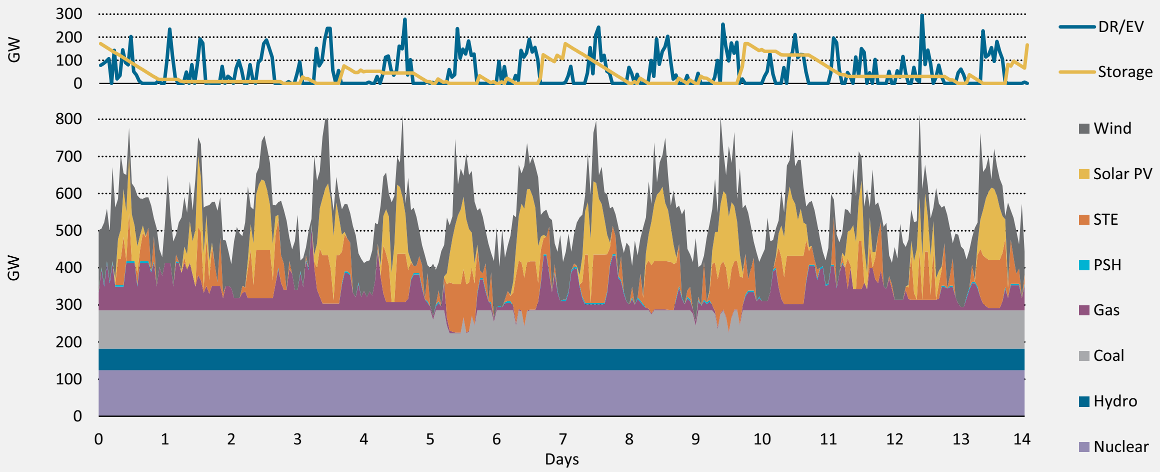
Technologies are described by their technical and economic parameters, such as conversion efficiencies or specific investment costs. Learning curves are used for new technologies to link future cost developments with cumulative capacity deployment.

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



Note: PV = photovoltaics; STE = solar thermal electricity; PSH = pumped storage hydropower; DR = demand response.

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 technology-rich stock accounting simulation models that cover three energy-intensive sectors (chemicals and petrochemicals, pulp and paper, and aluminium) and TIMES-based linear optimisation models[1] for the two remaining energy-intensive sectors (iron and steel, and cement). 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 of 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 is 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 portfolio for each country or region are characterised in the base year based on relevant energy use and material production statistics for each industrial energy-intensive 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 on 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.

MoMo for transport sector

The Mobility Model (MoMo) is a technical-economic spreadsheet model that allows detailed projections of transport activity, vehicle activity, energy demand, and CO_2 and pollutant emissions in different policy scenarios to 2050. The mobility model currently covers:

- 29 countries and regions
- passenger and freight services

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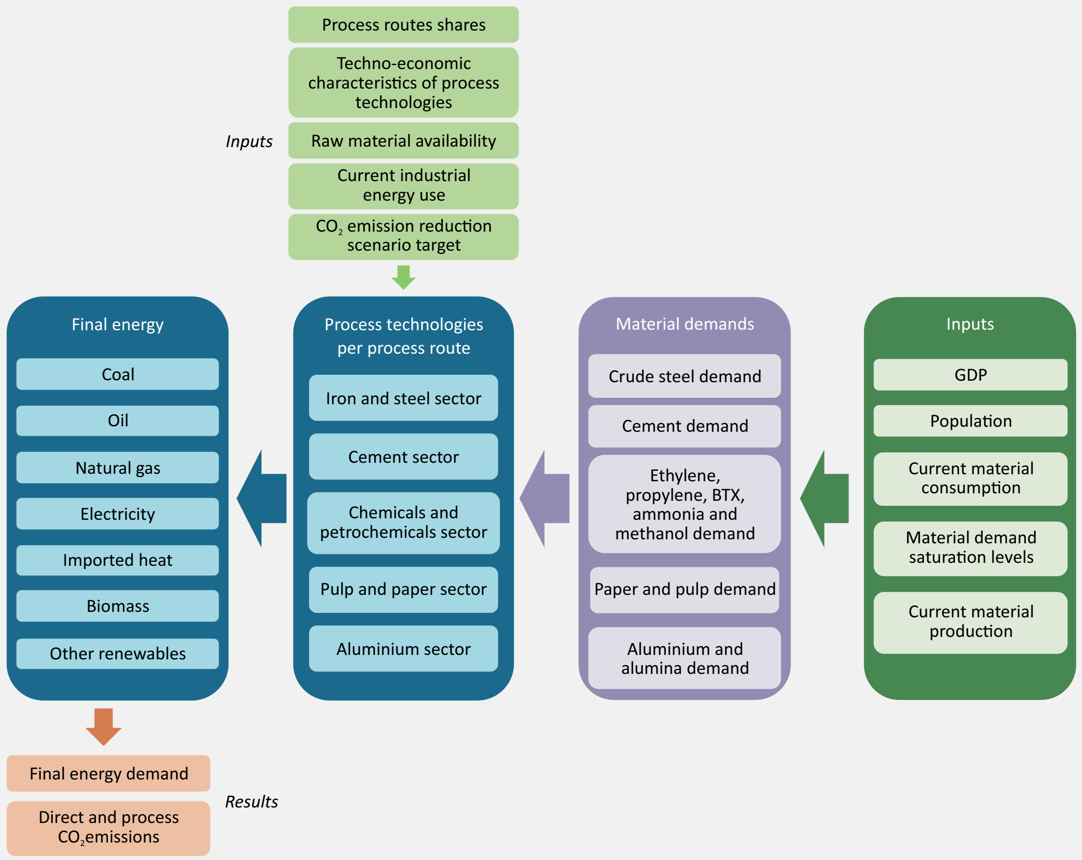
[1] The ETP-Industry model is currently in a transition phase as it is being migrated to the TIMES modelling platform.

[2] BTX includes benzene, toluene and xylene.

- all transport modes except pipelines (road, rail, shipping and air)
- several road vehicle types (2- and 3-wheelers, passenger cars, light trucks, medium and heavy freight trucks, buses)
- a wide number of powertrain technologies (internal combustion engines, and hybrid electric, plug-in hybrid electric, electric and fuel cell powertrains)
- related fuel supply options (petroleum gasoline and diesel, biofuel and synthetic fuel alternatives to liquid fuels, gaseous fuels including natural gas and hydrogen, and electricity).

Figure A.4 Structure of industry model

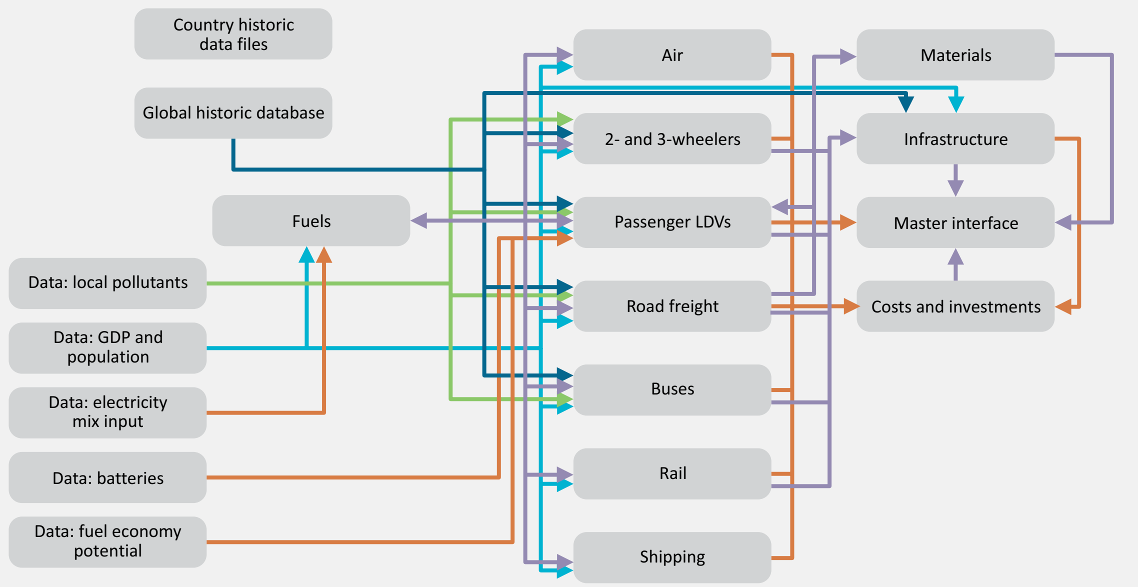


Key point *Based on socio-economic assumptions and statistical information, the industry model projects material demands, which then determine the final energy consumption of the sector depending on the energy performance of process technologies within each of the available production routes.*

MoMo also takes into account of the cost of vehicles, fuels and transport infrastructure, as well as material required for the construction of vehicles, related energy needs, and CO_2 and pollutant emissions.

To ease the manipulation and implementation of the modelling process, MoMo is split into several modules that can be updated independently. Figure A.5 provides a representation of how the modules are organised and how they communicate.

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.*

Integrating assumptions on technology availability and cost at different points 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, Cazzola and Cuenot, 2009).

To ensure consistency among the vehicles, 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.

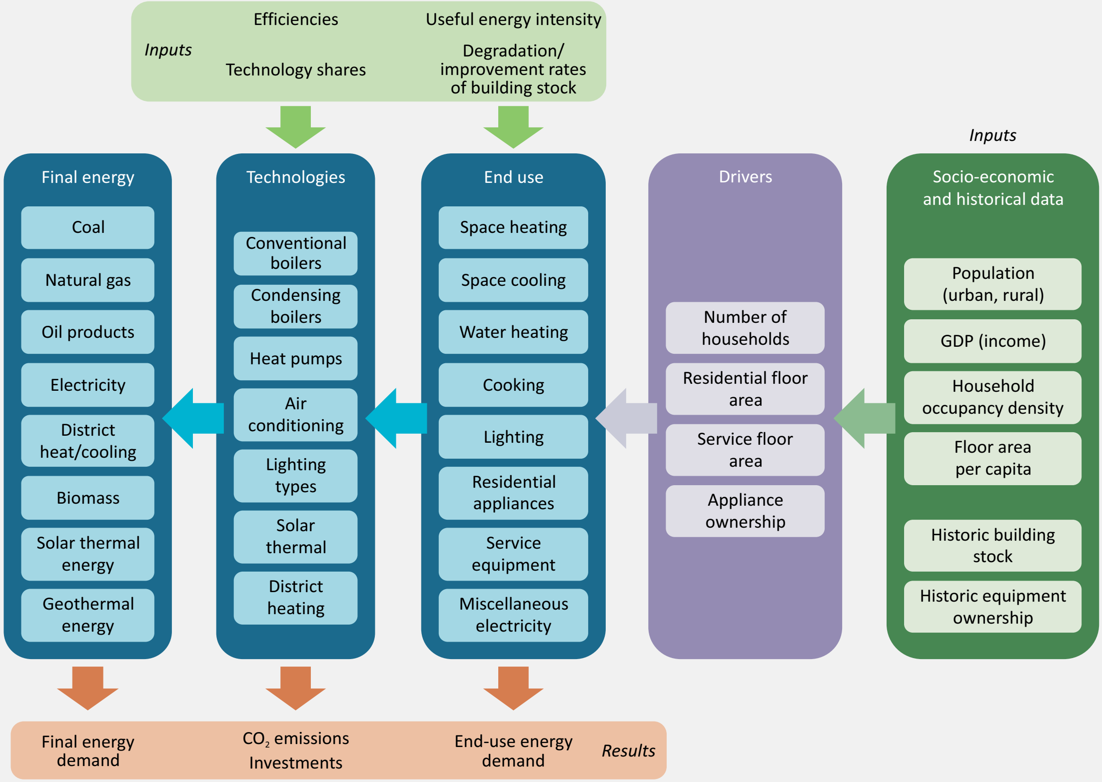
For each scenario, this model supports a comparison of marginal costs of technologies and aggregates to total cost across all modes and regions.

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.

Buildings sector model

The buildings sector is modelled using a global simulation stock accounting model, split into residential and services sub-sectors and applied across 31 countries/regions (Figure A.6). The residential sub-sector includes those activities related to individual dwellings. It covers all energy-using activities in apartments and houses, including space and water heating, cooling, lighting, and the use of appliances and electronics. The services sub-sector includes activities related to trade, finance, real estate, public administration, health, food and lodging, education, and commercial services. This is also referred to as the commercial and public service sector. It covers energy used for space heating, cooling and ventilation, water heating, lighting, and a number of other miscellaneous energy-using equipment, such as commercial appliances and cooking devices or office equipment.

Figure A.6 Structure of the buildings sector model



Key point *Starting from socio-economic assumptions, the buildings sector model determines first demand drivers and the related useful energy demands, which allows one to derive the final energy consumption depending on the characteristics of the technology options.*

For both sub-sectors, the model uses socio-economic drivers, such as income and population, to project floor space per capita and appliance ownership. As far as possible country statistics are used for floor area and appliance ownership rates in the base year, but especially for non-member economies of the Organisation for Economic Co-operation and Development (OECD), these data are more difficult to obtain, so in several cases these parameters have been estimated for the base year. The buildings floor area is differentiated by vintage, approximations based on other indicators (e.g. historical population) and used to estimate the vintage distributions if no statistical data are available for a country/region.

Based on the projections for floor area and appliance ownership, the model determines the useful energy demands, such as space or water heating, applying useful energy intensities, which take into account the vintage of the buildings 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 (e.g. space heating), a suite of different 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 2021 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. Assumed GDP projections for *ETP 2015* are unchanged to *ETP 2014*. An update of the GDP projections is planned for the *ETP 2016* edition, taking into account also revised power purchasing parities data for 2011, released by the World Bank's International Comparison Program in 2014.

Table A.1 Real GDP growth projections in *ETP 2015*

CAAGR (%)	2012-20	2020-30	2030-50	2012-50
World	4.1	3.4	2.7	3.2
OECD	2.3	2.1	1.7	1.9
Non-OECD	6.0	4.5	3.2	4.1
ASEAN	5.4	4.2	3.5	4.1
Brazil	4.0	3.8	2.7	3.3
China	8.1	4.9	2.9	4.5
European Union	1.5	1.8	1.5	1.6
India	6.7	6.5	5.1	5.8
Mexico	3.3	3.1	2.3	2.7
Russia	3.6	3.2	1.7	2.5
South Africa	3.1	2.6	2.2	2.5
United States	2.9	2.2	1.9	2.2

Notes: CAAGR = compounded average annual growth rate; ASEAN = Association of Southeast Asian Nations. Growth rates based on GDP in 2012 USD using purchasing power parity terms.
Source: IMF (2013), World Economic Outlook Database (April 2013 Edition), Washington, DC, www.imf.org/external/pubs/ft/weo/2013/01/weodata/index.aspx.

Population projections are based on the most recent United Nations population projections from 2013 (UNDESA, 2013).[3] The ETP scenarios use the medium-fertility variant of these projections, resulting in a global population increase by more than one third between 2012 and 2050.

Table A.2 Population projections in *ETP 2015*

(million)	2012	2020	2030	2040	2050
World	7 068	7 701	8 406	9 016	9 524
OECD	1 262	1 317	1 366	1 407	1 430
Non-OECD	5 806	6 385	7 035	7 609	8 095
ASEAN	610	665	721	762	785
Brazil	199	211	223	229	231
China	1 384	1 440	1 461	1 444	1 393
European Union	509	516	518	517	512
India	1 237	1 353	1 476	1 566	1 620
Mexico	121	132	144	152	156
Russia	143	140	134	127	121
South Africa	52	55	58	61	63
United States	322	342	367	387	405

Source: UNDESA (2013), World Population Prospects: The 2012 Revision, Medium-Fertility Variant, CD-ROM Edition.

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 2015* 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 fall 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.

The global marginal abatement costs for CO_2 to reach the reduction targets of the 4DS and 2DS are shown in Table A.4. These values represent the costs associated with the abatement measures to mitigate the last tonne of CO_2 emissions to reach the annual emissions target in a specific year. The global marginal abatement costs can be regarded as a benchmark CO_2 price allowing the comparison of the cost-effectiveness of mitigating options across technologies, sectors and regions. For the 2DS, with costs of up to USD 170/tCO_2 in 2050, it is more cost-effective to implement all mitigation measures up to that cost level rather than emitting the CO_2. In the 4DS, the less ambitious CO_2 reduction target results in significantly lower marginal abatement costs of up to USD 60/tCO_2.

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[3] The UN population projections are updated every two years, with the next projection to be released in the first half of 2015.

[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.

The costs shown for the 6DS reflect only the carbon price in the EU Emissions Trading Scheme (ETS) for electricity generation, industry and international aviation, which has been assumed to be continued after 2020.

Table A.3 Fossil fuel prices by scenario

		2013	2020	2025	2030	2035	2040	2045	2050
IEA crude oil import price (2013 USD/bbl)									
	2DS	106	105	104	102	101	100	99	98
	4DS	106	112	118	123	128	132	135	137
	6DS	106	116	128	139	147	155	161	167
OECD steam coal import price (2013 USD/t)									
	2DS	86	88	83	78	78	77	77	76
	4DS	86	101	105	108	110	112	114	116
	6DS	86	107	112	117	121	124	128	131
Gas (2013 USD/MBtu)									
United States price	2DS	3.7	5.1	5.5	5.9	6.0	6.1	6.0	6.0
	4DS	3.7	5.5	6.1	6.6	7.4	8.2	8.4	8.5
	6DS	3.7	5.5	6.2	6.8	7.7	8.5	8.9	9.1
Europe import price	2DS	10.6	10.5	10.3	10.0	9.6	9.2	9.1	9.0
	4DS	10.6	11.1	11.6	12.1	12.4	12.7	13.0	13.2
	6DS	10.6	11.5	12.4	13.2	13.6	14.0	14.6	15.0
Japan import price	2DS	16.2	13.6	13.1	12.6	12.3	12.0	11.9	11.8
	4DS	16.2	14.4	14.5	14.6	15.0	15.3	15.7	15.9
	6DS	16.2	15.0	15.7	16.3	16.9	17.5	18.2	18.8

Note: bbl = barrel; t = tonne; MBtu = million British thermal units.

Table A.4 Global marginal abatement costs by scenario

(USD/tCO_2)	2020	2030	2040	2050
2DS	30-50	80-100	120-140	140-170
4DS	10-30	20-40	30-50	40-60
6DS	20	30	40	50

Note: 6DS only assumes carbon pricing in the European Union for the sectors currently included in the ETS (electricity generation, industry and aviation), as well as in Korea for the power and industry sectors.

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Abbreviations and Acronyms

2DS	*ETP 2014* 2°C Scenario
4DS	*ETP 2012* 4°C Scenario
6DS	*ETP 2012* 6°C Scenario

A

ABCP	Associaçao Brasilieira de Cimento Portland
AC	alternating current
ACCA21	The Administrative Centre for China's Agenda 21
ACO	advanced catalytic olefins
AFR	alternative fuels and raw materials
AHWR	advanced heavy water reactors
AIS	accelerated improvement scenario
ANBERD	Analytical Business Enterprise Research and Development database
ANM	active network management
ANU	Australia National University
APEC	Asia-Pacific Economic Co-operation
ARPA-E	Advanced Research Projects Agency - Energy
ASEAN	Association of Southeast Asian Nations
ASU	air separation unit

B

BAT	best available technology
BCG	Boston Consulting Group
BECCS	bioenergy carbon capture and storage
BF	blast furnace
BF-TGR	blast furnace with top gas recovery
BLG	black liquor gasification
BNEF	Bloomberg New Energy Finance
BOF	basic oxygen furnace
BOP	balance of plant
BOS	balance of system
BPT	best practice technology
BSRIA	Building Services Research and Information Association
BYD	BYD Auto Co., Ltd.

C

CAAGR	compounded average annual growth rate
CAAM	China Association of Automobile Manufactures
CAES	compressed air energy storage
CAGS	China-Australia Geological Storage of CO_2
CAS	Chinese Academy of Sciences

	CASS	Chinese Academy of Social Science
	CBM	coalbed methane
	CCGT	combined-cycle gas turbine
	CCS	carbon capture and storage
	CCUS	carbon capture utilisation and storage
	CDM	Clean Development Mechanism
	CEM	Clean Energy Ministerial
	CEPI	Confederation of European Paper Industries
	CERC	Central Electricity Regulatory Commission
	CES	clean energy system
	CFD	contracts for difference
	CFL	compact fluorescent lamp
	CFPP	coal-fired power plant
	ChinaIRN	China Industry Research Net
	CHP	combined heat and power
	CIC	Climate Innovation Centre
	CIF	cost insurance freight
	CIS	continuous improvement scenario
	CLC	chemical looping combustion
	CNOOC	China National Offshore Oil Corporation
	CNY	Chinese yuan
	CO_2	carbon dioxide
	COACH	China-EU Carbon Capture and Storage Co-operation
	COG	coke oven gas
	COP	Conference of the Parties
	CPIA	China Photovoltaic Industry Alliance
	CPN	China Plan Net
	CPV	concentrating photovoltaics
	CREIA	Chinese Renewable Energy Industries Association
	CSG	China Southern Power Grid
	c-Si	crystalline silicone
	CSLF	Carbon Sequestration Leadership Forum
	CSP	concentrated solar power
	CSR	China South Locomotive & Rolling Stock Corporation Limited
	CTA	Technical Centre of Aeronautics
	CTC	Climate Technology Centre
	CTP	Climate Technology Program
D	DC	direct current
	Dechema	Gesellschaft für Chemische Technik und Biotechnologie e. V.
	DH	district heating
	DHC	district heating and cooling
	DNI	direct normal irradiance
	DoD	depth of discharge

DCR	domestic content requirement
DRI	direct reduced iron
DSG	direct steam generation
DSM	demand-side management

E

EAF	electric arc furnace
EBC	Energy in Buildings and Communities
EC	European Commission
ECRA	European Cement Research Academy
EEDI	energy efficiency design index
EEG	Erneuerbare-Energien-Gesetz, German Renewable Energy Act
EES	energy efficient strategies
EMS	energy management systems
EOR	enhanced oil recovery
ESC	equivalent storage cost
ESCII	energy sector carbon intensity index
ESEC	European Steel Environment and Energy Congress
ESS	energy storage system
ESTEP	European Steel Technology Platform
ETSAP	Implementing Agreement for a Programme of Energy Technology Systems Analysis
ETP	*Energy Technology Perspectives*
ETS	Emissions Trading System
EU	European Union
EV	electric vehicle
EVI	Electric Vehicles Initiative

F

FCEV	fuel cell electric vehicle
FCV	fuel cell vehicle
FDI	foreign direct investment
FFV	flex-fuel vehicles
FiT	feed-in tariff
FKA	Forschungsgesellschaft Kraftfahrwesen mbH Aachen
FPA	Forest Products Association of Canada
FSU	former Soviet Union
FTA	Free Trade Agreement
FYP	five-year plan

G

GBI	generation-based incentive
GCCSI	Global CCS Institute
GDP	gross domestic product
GEF	Global Environment Facility
GFEI	Global Fuel Economy Initiative

GHG	greenhouse gas
GHG IA	Implementing Agreement for a Co-operative Programme on Technologies Relating to Greenhouse Gas Derived from Fossil Fuels Use
GHI	global horizontal irradiance
GIVAR	grid integration of variable renewables
GNI	global normal irradiance

H

H2020	Horizon 2020
HDV	heavy-duty vehicle
HEV	hybrid electric vehicle
HP	high pressure
HPWH	heat pump water heater
HRSG	heat recovery steam generator
HTS	high-temperature superconductors
HV	high voltage
HVC	high-value chemical
HVAC	high-voltage alternating current
HVDC	high-voltage direct current

I

IAEA	International Atomic Energy Agency
ICAO	International Civil Aviation Organization
ICCA	International Council of Chemical Associations
ICCT	International Council on Clean Transportation
ICE	internal combustion engine
ICT	information and communication technology
IDC	interest during construction
IEA	International Energy Agency
IESA	India Energy Storage Alliance
IFA	International Fertilizer Industry Association
IFC	International Finance Corporation
IFIT	Investments in Forest Industry Transformation
IGCC	integrated gasification combined cycle
IISD	International Institute for Sustainable Development
IMO	International Maritime Organization
INDC	Intended Nationally Determined Contribution
IOSC	The Information Office of the State Council (China)
IP	intellectual property
IPP	independent power producer
IPCC	Intergovernmental Panel on Climate Change
IPEEC	International Partnership for Energy Efficiency Co-operation
IPR	intellectual property rights
IRENA	International Renewable Energy Agency
ISCC	integrated solar combined-cycle

ISO	International Organisation for Standardisation
ITC	International Trade Centre
IUCN	International Union for Conservation of Nature

J

JET	Japan Electrical Safety and Environment Technical Laboratories
JISF	Japan Iron and Steel Federation
JNNSM	Jawaharlal Nehru National Solar Mission
JPO	Japan Patent Office
JV	joint venture

K

KRICT	Korean Research Institute of Chemical Technologies
KFW	Kreditaufalt Fur Wiedenraufbau

L

LBNL	Lawrence Berkeley National Laboratory
LCA	life-cycle assessment
LCOE	levelised cost of electricity
LCR	local content requirement
LCV	light commercial vehicle
LED	light-emitting diode
LHV	lower heating value
LIS	low impact steel
LKAB	Luossavaara-Kiirunavaara AB
LNG	liquefied natural gas
low-e	low emissivity
LP	low pressure

M

MDB	multilateral development banks
MEP	Ministry of Environmental Protection (China)
MEPS	minimum energy performance standards
METI	Ministry of Economy, Trade and Industry (Japan)
MF	multiple family
MFT	medium freight truck
MIIT	Ministry of Industry and Information Technology (China)
MLR	Ministry of Land and Resources (China)
MOF	Ministry of Finance (China)
MOFCOM	Ministry of Commerce (China)
MOHURD	Ministry of Housing, Urban and Rural Development (China)
MoMo	mobility model
MOST	Ministry of Science and Technology (China)
MTO	methanol-to-olefin
MVE	monitor, verify and enforce

N

NaS	sodium sulphide
NASA	National Aeronautics and Space Administration

	NBS	National Bureau of Statistics (China)
	NDB	national development bank
	NDRC	National Development and Reform Commission
	NEA	National Energy Administration (China)
	NEA	Nuclear Energy Agency
	NEDO	New Energy and Industrial Technology Development Organization
	NETL	National Energy Technology Laboratory
	NFTTC	National Fund for Technology Transfer and Commercialization
	NGCC	natural gas combined-cycle
	NHTSA	National Highway Traffic Safety Administration
	NPV	net present value
	NRC	National Research Council
	NRCAN	Natural Resources Canada
	NREL	National Renewable Energy Laboratories
	NSF	National Science Foundation
	NZEB	near-zero-energy building
	NZEC	near-zero emissions coal
O	O&M	operation and maintenance
	OCGT	open-cycle gas turbine
	OECD	Organisation for Economic Co-operation and Development
	OIES	Oxford Institute for Energy Studies
P	PCM	phase-change material
	PFBR	pressurised fast breeder reactor
	PHEV	plug-in hybrid-electric vehicle
	PHS	pumped hydro storage
	PHWR	pressurised heavy water reactor
	PLDV	passenger light-duty vehicle
	PMSM	permanent-magnet synchronous motor
	PMU	phasor measurement unit
	POSCO	Pohang Iron and Steel Company
	PPA	power purchase agreement
	PPP	public-private partnership
	PPP	purchasing power parity (Ch. 8)
	PSA	pressure swing adsorption
	PTC	production tax credit
	PV	photovoltaic
	PWR	pressurised water reactor
Q	QR	quick response

R

R&D	research and development
RD&D	research, development and demonstration
RDD&D	research, development, demonstration and deployment
RFCS	Research Fund for Coal and Steel
RIST	Research Institute of Industrial Science and Technology
R&M	research and markets
RPS	renewable portfolio standards
RRECL	Rajasthan Renewable Energy Corporation Limited

S

S&T	science and technology
SASAC	State-owned Assets Supervision and Administration Commission of the State Council (China)
SEAD	super-efficient equipment and appliance deployment
SC	steam cycle
SCPC	supercritical pulverized coal
SEI	strategic emerging industry
SEVIA	State-owned Enterprise Electric Vehicle Industry Alliance
SF	single family
SGCC	State Grid Corporation of China
SHC	solar heating and cooling
SICCS	Sino-Italy CCS Technology Co-operation Project
SME	small and medium-sized enterprise
SMES	superconducting magnet energy storage
SMRC	short-run marginal cost
SNIC	Sindicato Nacional da Industria do Cimento
SOE	state-owned enterprise
SONI	System Operator for Northern Ireland
SPIRE	Sustainable Process Industry through Resource and Energy Efficiency
SR	smelting reduction
SSL	solid-state lighting
STB	set-top box
STE	solar thermal electricity
SusChem	European Technology Platform for Sustainable Chemistry

T

T&D	transmission and distribution
TCEP	Tracking Clean Energy Progress
TCM	thermo-chemical heat
TEC	Technology Executive Committee
TF	thin film
TGC	tradable green certificate
TIMES	The Integrated MARKAL-EFOM System
TOD	time-of-delivery
TOU	time-of-use

TPES	total primary energy supply
TRIM	Trade-Related Investment Measure
TRL	technology readiness level
TSA	temperature swing adsorption
TSO	transmission system operator
TTF	title transfer facility

U

UCG	underground coal gasification
UHVDC	ultra-high-voltage direct current
UK	United Kingdom
ULCOS	ultra-low carbon dioxide steelmaking
UMPP	ultra-mega power plant
UNFCCC	United Nations Framework Convention on Climate Change
UNIDO	United Nations Industrial Development Organization
USD	United States dollar
US DOE	United States Department of Energy
US EPA	United States Environmental Protection Agency
USCPC	ultra-supercritical pulverised coal
USPTO	US Patent and Trademark Office
UTES	underground thermal energy storage

V

VCSF	venture capital "sub-fund"
VDEh	Association of German Steel Manufacturers
VRE	variable renewable energy

W

WACC	weighted average capital cost
WAMPAC	wide-area monitoring, protection and control
WBCSD	World Business Council for Sustainable Development
WEO	*World Energy Outlook*
WHO	World Health Organization
WHR	waste heat recovery
WLTP	worldwide harmonised light vehicle test procedure
Worldsteel	The World Steel Association
WTO	World Trade Organization

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. Four-wheelers are not homologated to drive on motorways, such as all terrain vehicles.
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% lifecycle 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 energy derived from the conversion of biomass where biomass may be used directly, as fuel, or processed into liquids and gases.
	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.
	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, is the amount of power produced, transmitted, distributed or used at a given instant.
	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.
	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, and oil crops, like canola and palm, and in some cases animal fats.
Corex	A smelting-reduction process developed by Siemens VAI for manufacture of hot metal from iron ore and coal in which the iron ore is pre-reduced in a reduction shaft using offgas from the melter-gasifier before being introduced into the melter-gasifier.

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.

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 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 an economic or physical 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 made from starches and sugars, but second generation technologies will allow it to be made from cellulose and hemicellulose, the fibrous material that makes up the bulk of most plant matter.
F	FINEX	A smelting-reduction process developed by Pohang Iron and Steel Company (POSCO) in collaboration with Siemens VAI, where iron ore fines are pre-reduced in a series of fluidised bed reactors before being introduced to the melter-gasifier.
	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 to maintain 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 or other gaseous carbons 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.

HIsarna	A smelting reduction process being developed by the European Ultra-Low Carbon Dioxide Steelmaking (ULCOS) programme, which combines the HIsmelt process with an advanced Corus cyclone converter furnace. All process steps are directly hot-coupled, avoiding energy losses from intermediate treatment of materials and process gases.
Hydropower	Hydropower refers 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

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 vehicles aimed at the mobility of persons on all types of roads, up to nine persons per vehicle and 3.5t 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.
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 includes biomass and waste, geothermal, hydropower, solar photovoltaic, concentrating solar power, wind and marine (tide and wave) energy for electricity and heat generation.
Road mass transport	See “Buses and minibuses”.

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). The final consumption of the transport sector includes international marine and aviation bunkers.
Total primary energy demand (TPED)	Total primary energy demand (TPED) represents domestic demand only and is broken down into power generation, other energy sector and total final consumption.
Total primary energy supply	TPES is the total amount of energy supplied to the energy system, at the domestic level it is equivalent to total primary energy demand. Total primary energy supply is made up of primary energy production + imports - exports ± stock changes. Stock changes reflect the difference between opening stock levels on the first day of the year and closing levels on the last day of the year of stocks on national territory. A stock build is a negative number, and a stock draw is a positive number.

	Traditional biomass use	Traditional biomass use 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.
V	Venture capital	Venture capital is a form of private capital typically provided for early stage, high potential growth companies.

Sector definitions

Buildings	Buildings includes energy used in residential, commercial and institutional buildings. Building energy use includes space heating and cooling, water heating, lighting, appliances, cooking and miscellaneous equipment (such as office equipments 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 industries and the energy losses in converting primary energy into a form that can be used in the 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 Industry.
Industry	Industry includes fuel used within the manufacturing and construction industries. 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, 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 is the process of generating electricity and/or heat from other sources of primary energy. Both main activity producer plants and so-called autoproducer plants that produce electricity or heat for their own use are included.
Transport	Transport includes all the energy used once transformed (tank-to-wheel); international marine and aviation bunkers is shared among countries based on the statistics available. Energy use and emissions related to 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, 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, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden and 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 United States.

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[1] Because only aggregated data were available until 2011, the data for Sudan also include South Sudan.

[2] Individual data is not available for: Burkina Faso, Burundi, Cape 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. Data is estimated in aggregate for these regions.

[3] Individual data is not available for: Afghanistan, Bhutan, Cook Islands, East Timor, Fiji, French Polynesia, Kiribati, Lao PDR, Macau, Maldives, New Caledonia, Palau, Papua New Guinea, Samoa, Solomon Islands, Tonga and Vanuatu. Data is 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 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 is 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 is 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, Netherlands, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey and United Kingdom.
Other developing Asia	Non-OECD Asia regional grouping excluding China and India.

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[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 GolanHeights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

Units of measure

Unit prefix	μ	micro (10^{-6}, millionth)
	c	centi (10^{-2}, hundredth)
	E	exa (10^{18}, quintillion)
	G	giga (10^{9}, billion)
	k	kilo (10^{3}, thousand)
	m	milli (10^{-3}, thousandth)
	M	mega (10^{6}, million)
	P	peta (10^{15}, quadrillion)
	T	tera (10^{12}, trillion)
Area	ha	hectare
	km^2	square kilometre
	m^2	square metre
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	tce	tonne of coal equivalent
	Mtce	million tonnes of coal equivalent (equals 0.7 Mtoe)
	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
Mass	kg	kilogramme
	t	tonne
	kt	kilotonne (1 tonne x 10^3)
	Mt	million tonnes (1 tonne x 10^6)
Monetary	CNY	Chinese yuan
	CNY million	1 Chinese yuan x 10^6
	CNY billion	1 Chinese yuan x 10^9
	USD million	1 US dollar x 10^6
	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/h	kilometres per hour
	lge	litre of gasoline-equivalent
	mpg	miles per gallon
	pkm	passenger kilometre
	tkm	tonne kilometre
	vkm	vehicle kilometre

Table C.1 General conversion factors for energy

Convert to:	TJ	Gcal	Mtoe	MBtu	GWh
From:	multiply by:				
TJ	1	238.8	2.388×10^{-5}	947.8	0.2778
Gcal	4.1868×10^{-3}	1	10^{-7}	3.968	1.163×10^{-3}
Mtoe	4.1868×10^{4}	10^{7}	1	3.968×10^{7}	11 630
MBtu	1.0551×10^{-3}	0.252	2.52×10^{-8}	1	2.931×10^{-4}
GWh	3.6	860	1.6×10^{-5}	3 412	1

Note: There is no generally accepted definition of boe; typically the conversion factors used vary from 7.15 to 7.35 boe per toe.

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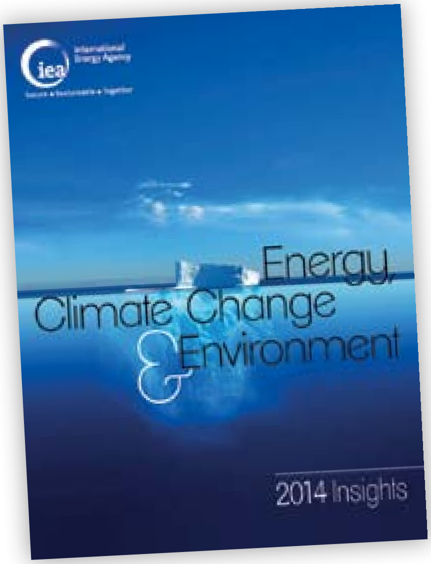
Explore the data behind *Energy Technology Perspectives 2015*

www.iea.org/etp2015

The IEA is expanding the availability of data used to create the *Energy Technology Perspectives* publication. Please visit the restricted area of the ETP website, www.iea.org/etp2015. There you will find many of the figures, graphs and tables in this book available for download, along with much more material. The website is evolving and will be continuously updated. Your username is “etp2015” and password “35X2015etp”.

Also from the IEA



Energy, Climate Change and Environment: 2014 Insights, provides in-depth analysis of selected policy questions at the energy-climate interface: how to address (i.e., "unlock") existing high-emissions infrastructure, the design of cost-effective emissions trading systems, the use of energy-specific metrics for near- and long-term decarbonisation, and how local air pollution policies may help reconcile energy and climate goals. An update of key statistics for ten world regions is also provided. www.iea.org/ecce

New releases

There are no quick fixes to long-term energy challenges. To find solutions, governments and industry benefit from sharing resources and results. For this reason the IEA supports multilateral experts' groups on a wide range of technologies. Recent achievements of these groups are synthesised in the biennial ***Energy Technology Initiatives***. The 2015 edition marks the 40th anniversary. Forthcoming 4th quarter 2015 www.iea.org/techinitiatives

The ***IEA Policies and Measures Databases*** contain information on policies and measures to reduce greenhouse gas emissions, improve energy efficiency and support renewable energy. This online service complements the policy analysis carried out by the IEA and covers all IEA member countries and many non-member countries too. Delegates from IEA member countries are given the opportunity to review the information twice a year. www.iea.org/policiesandmeasures

Capturing the Multiple Benefits of Energy Efficiency goes beyond the traditional analysis of energy demand reduction and climate change mitigation. with its potential to enhance economic prosperity, social development, sustainability and energy security, the multiple benefits perspective can reposition energy efficiency in the policy mainstream. www.iea.org/multiplebenefits

IEA Technology Roadmaps help set the agenda for development and deployment of key low-carbon energy technologies. These free publications identify priority actions needed to support technological advances and uptake by society in alignment with the ETP 2DS vision. As of May 2015, 20 global roadmaps have been published, covering topics including buildings, CCS, electric vehicles, nuclear, solar and storage. Further global and regional roadmaps, as well as How2Guides, are in production. More details at: www.iea.org/roadmaps

For more information, please visit www.iea.org

IEA PUBLICATIONS, 9 rue de la Fédération, 75739 PARIS CEDEX 15
Typeset in France by Jouve and printed in France by CORLET, May 2015
(612015051E1) ISBN: 9789264233423
Photo credits: Brewbooks, Graphic Obsession, NASA/Goddard Space Flight Center/Reto Stöckli, NASA/Earth Observatory, NASA/JPL-Caltech/MSSS, NASA/Bill Ingalls, NASA/Bridget R. Caswell, Craig Mayhew and Robert Simmon NASA GSFC

Energy Technology Perspectives 2015

Mobilising Innovation to Accelerate Climate Action

As climate negotiators work towards a deal that would limit the increase in global temperatures, interest is growing in the essential role technology innovation can and must play in enabling the transition to a low-carbon energy system. Indeed, recent success stories clearly indicate that there is significant and untapped potential for accelerating innovation in clean technologies if proper policy frameworks are in place.

In an especially timely analysis, the 2015 edition of *Energy Technology Perspectives* (*ETP 2015*) examines innovation in the energy technology sector and seeks to increase confidence in the feasibility of achieving short- and long-term climate change mitigation targets through effective research, development, demonstration and deployment (RDD&D). *ETP 2015* identifies regulatory strategies and co-operative frameworks to advance innovation in areas like variable renewables, carbon capture and storage, and energy-intensive industrial sectors. The report also shows how emerging economies, and China in particular, can foster a low-carbon transition through innovation in energy technologies and policy. Finally, *ETP 2015* features the IEA annual *Tracking Clean Energy Progress* report, which this year shows that efforts to decarbonise the global energy sector are lagging further behind.

By setting out pathways to a sustainable energy future and by incorporating detailed and transparent quantitative modelling analysis and well-rounded commentary, *ETP 2015* and its series of related publications are required reading for experts in the energy field, policy makers and heads of governments, as well as business leaders and investors.

ETP 2015 *purchase includes extensive downloadable data, figures and visualisations. For more information, please visit* **www.iea.org/etp2015**

€120
ISBN: 978-92-64-23342-3
(61 2015 05 1E1)

Design by MSDS | ms-ds.com
Typeset by Jouve
Photo credit: flickr.com | Brewbooks