World Energy Model Documentation

October 2021

International Energy Agency

World Energy Model Documentation

October 2021

International
Energy Agency

Contents

1 Background

Since 1993, the International Energy Agency (IEA) has provided medium- to long-term energy projections using the World Energy Model (WEM). The model is a large-scale simulation model designed to replicate how energy markets function and is the principal tool used to generate detailed sector-by-sector and region-by-region projections for the *World Energy Outlook* (*WEO*) scenarios. Updated every year and developed over many years, the model consists of three main modules: final energy consumption (covering residential, services, agriculture, industry, transport and non-energy use); energy transformation including power generation and heat, refinery and other transformation – such as Coal to Liquids or hydrogen production; and energy supply (oil, natural gas and coal). Outputs from the model include energy flows by fuel, investment needs and costs, CO_2 emissions and end-user prices.

The WEM is a very data-intensive model covering the whole global energy system. Much of the data on energy supply, transformation and demand, as well as energy prices is obtained from the IEA's own databases of energy and economic statistics (http://www.iea.org/statistics) and through collaboration with other institutions. For example, for the *Net Zero by 2050: A Roadmap for the Global Energy Sector* publication, results from both the WEO and Energy Technology Perspectives (ETP) models have been combined with those from the International Institute for Applied Systems Analysis (IIASA) – in particular the Greenhouse Gas - Air Pollution Interactions and Synergies (GAINS) model – to evaluate air pollutant emissions and resultant health impacts. And, for the first time, results were combined with the IIASA's Global Biosphere Management Model (GLOBIOM) to provide data on land use and net emissions impacts of bioenergy demand. The WEO and ETP models have also been linked to the Global Integrated Monetary and Fiscal (GIMF) model of the International Monetary Fund (IMF) to assess the impacts of changes in investment and spending on global GDP. The WEM also draws data from a wide range of external sources which are indicated in the relevant sections of this document.

The WEM is constantly reviewed and updated to ensure its completeness and relevancy. The development of the WEM benefits from expert review within the IEA and beyond and the IEA works closely with colleagues in the modelling community, for example, by participating in and hosting regularly the International Energy Workshop. The analysis for the Net Zero Emissions by 2050 Scenario was informed by discussions with modelling teams from across the world, including from China, the United States, Japan, the United Kingdom, the European Union and the IPCC.

The current version of WEM covers energy developments up to **2050** in 26 regions. Depending on the specific module of the WEM, individual countries are also modelled: 12 in demand; 102 in oil and natural gas supply; and 19 in coal supply (see Annex 1). The WEM is designed to analyse:

- ***Global and regional energy prospects:*** these include trends in demand, supply availability and constraints, international trade and energy balances by sector and by fuel in the projection horizon.
- ***Environmental impact of energy use:*** CO_2 emissions from fuel combustion are derived from the projections of energy consumption. CO_2 process emissions have been estimated based on the production of industrial materials while non-CO_2 emissions originating from non-energy sectors rely on the scenarios from the IPCC 5th Assessment Report scenario database. Methane from oil and gas emissions are assessed through bottom-up estimates and direct emissions measurements (see Methane Tracker 2021). Local pollutants are also estimated linking WEM with the GAINS model of the International Institute for Applied Systems Analysis (IIASA).
- ***Effects of policy actions and technological changes:*** alternative scenarios analyse the impact of a range of policy actions and technological developments on energy demand, supply, trade, investments and emissions.

- ***Investment in the energy sector:*** WEM evaluates investment requirements in the fuel supply chain to satisfy projected energy demand. It also evaluates demand-side investment requirements, including energy efficiency, electrification and other end-use sectors including industrial carbon capture and storage.
- ***Modern energy access prospects:*** These include trends in access to electricity and clean cooking facilities. It also evaluates additional energy demand, investments and CO_2 emissions due to increased energy access.

WEO scenarios

The *World Energy Outlook* makes use of a scenario approach to examine future energy trends relying on the WEM. For the *World Energy Outlook 2021 (WEO-2021)*, detailed projections for four scenarios were modelled: the Announced Pledges Scenario, the Net Zero Emissions by 2050 Scenario, the Stated Policies Scenario and the Sustainable Development Scenario (presented selectively across WEO-2021). The scenarios are based on rigorous modelling and analysis, reflecting the latest energy data, policy announcements, investment trends, and technology developments. The formulation of the scenarios takes into consideration the full diversity of country circumstances, resources, technologies and potential policy choices in its examination of future scenarios. In contrast to the 2020 edition of the WEO, we do not vary the assumptions about public health and economic recovery implications across the scenarios.

Table 1 Definitions and objectives of the WEO-2021 scenarios

	Net Zero Emissions by 2050 Scenario	Announced Pledges Scenario	Stated Policies Scenario	Sustainable Development Scenario
Definitions	A scenario which sets out a narrow but achievable pathway for the global energy sector to achieve net zero CO_2 emissions by 2050. It doesn't rely on emissions reductions from outside the energy sector to achieve its goals.	A scenario which assumes that all climate commitments made by governments around the world, including Nationally Determined Contributions (NDCs) and longer-term net zero targets, will be met in full and on time.	A scenario which reflects current policy settings based on a sector-by-sector assessment of the specific policies that are in place, as well as those that have been announced by governments around the world	An integrated scenario specifying a pathway aiming at: ensuring universal access to affordable, reliable, sustainable and modern energy services by 2030 (SDG 7); substantially reducing air pollution (SDG 3.9); and taking effective action to combat climate change (SDG 13).
Objectives	To show what is needed across the main sectors by various actors, and by when, for the world to achieve net zero energy related and industrial process CO_2 emissions by 2050 while meeting other energy-related sustainable development goals.	To show how close do current pledges get the world towards the target of limiting global warming to 1.5 °C, it highlights the "ambition gap" that needs to be closed to achieve the goals agreed at Paris in 2015	To provide a benchmark to assess the potential achievements (and limitations) of recent developments in energy and climate policy.	To demonstrate a plausible path to concurrently achieve universal energy access, set a path towards meeting the objectives of the Paris Agreement on climate change and significantly reduce air pollution.

The Net Zero Emissions by 2050 Scenario (NZE). This is a normative IEA scenario that shows a narrow but achievable pathway for the global energy sector to achieve net zero CO_2 emissions by 2050, with advanced economies reaching net zero emissions in advance of others. This scenario also meets key energy-related United Nations Sustainable Development Goals (SDGs), in particular by achieving universal energy access by 2030 and major improvements in air quality. The NZE does not rely on emissions reductions from outside the energy sector to achieve its goals, but assumes that non-energy emissions will be reduced in the same proportion as energy emissions. It is consistent with limiting the global temperature rise to 1.5 °C without a temperature overshoot (with a 50% probability).

The **Announced Pledges Scenario (APS**) appears for the first time in this WEO. It takes account of all of the climate commitments made by governments around the world, including NDCs as well as longer term net zero targets, and assumes that they will be met in full and on time. The global trends in this scenario represent the cumulative extent of the world's ambition to tackle climate change as of mid-2021. The remaining difference in global emissions between the outcome in the APS and the normative goals in the NZE or the Sustainable Development Scenario shows the "ambition gap" that needs to be closed to achieve the goals agreed at Paris in 2015.

The **Stated Policies Scenario (STEPS)** provides a more conservative benchmark for the future, because it does not take it for granted that governments will reach all announced goals. Instead, it takes a more granular, sector-by-sector look at what has actually been put in place to reach these and other energy-related objectives, taking account not just of existing policies and measures but also of those that are under development. For example, the new "Fit for 55" package of measures announced by the European Commission in July 2021 provides the detailed underpinnings for the European Union to reach its new 2030 emissions reduction target (a 55% reduction in emissions by 2030 compared with 1990 levels), and this is sufficient to bring the near-term EU trajectory in the STEPS close to that in the APS. The STEPS explores where the energy system might go without a major additional steer from policy makers. As with the APS, it is not designed to achieve a particular outcome.

An additional scenario referenced in WEO-2021 is the **Sustainable Development Scenario (SDS)**. As a "well below 2 °C" pathway, the SDS represents a gateway to the outcomes targeted by the Paris Agreement. Like the NZE, the SDS is based on a surge in clean energy policies and investment that puts the energy system on track for key SDGs. In this scenario, all current net zero pledges are achieved in full and there are extensive efforts to realise near-term emissions reductions; advanced economies reach net zero emissions by 2050, China around 2060, and all other countries by 2070 at the latest. Without assuming any net negative emissions, this scenario is consistent with limiting the global temperature rise to 1.65 °C (with a 50% probability). With some level of net negative emissions after 2070, the temperature rise could be reduced to 1.5 °C in 2100.

The WEM scenarios allow us to evaluate the impact of specific policies and measures on energy demand, production, trade, investment needs, supply costs and emissions. A policies and measures database, detailing policies addressing renewable energy, energy efficiency, and climate change, supports the analysis. This database is available at: http://www.iea.org/policies/.

Box 1: An integrated approach to energy and sustainable development in the NZE and SDS scenarios

The NZE and SDS scenarios integrates three key objectives of the UN 2030 Agenda for Sustainable Development: universal access to modern energy services by 2030 (embodied in SDG 7), reducing health impacts of air pollution (SDG 3.9), and action to tackle climate change (SDG 13). As a first step, we use the WEM to assess how the energy sector would need to change to deliver universal access to modern energy services by 2030. To analyse electricity access, we combine cost-optimisation with new geospatial analysis that takes into account current and planned transmission lines, population density, resource availability and fuel costs.

Second, we consider outdoor air pollution and climate goals. The policies necessary to achieve the multiple SDGs covered in the Sustainable Development Scenario are often complementary. For example, energy efficiency and renewable energy significantly reduce local air pollution, particularly in cities, while access to clean cooking facilitated by liquefied petroleum gas also reduces overall greenhouse gas emissions by reducing methane emissions from incomplete combustion of biomass as well as by reducing deforestation. Trade-offs can also exist, for example between electric vehicles reducing local air pollution from traffic, but at the same time increasing overall CO_2 emissions if there is not a parallel effort to decarbonise the power sector. Ultimately, the balance of potential synergies or trade-offs depends on the route chosen to achieve the energy transition, making an integrated, whole-system approach to scenario building essential. The multiple objectives of the Sustainable Development Scenario mean that technology choices differ from other scenarios solely driven by climate considerations. The emphasis of the Sustainable Development Scenario is on technologies with short project lead times in the power sector in particular, such as renewables, while the longer-term nature of climate change allows for other technology choices. Modern uses of biomass as a decarbonisation option is also less relevant in the NZE and SDS scenarios than in a single-objective climate scenario. This is because biomass is a combustible fuel, requiring post-combustion control to limit air pollutant emissions and – depending on the region in question - making it more costly than alternatives.

Since *WEO-2018* the Sustainable Development Scenario, and now the NZE as well, also looks at the implications for the energy sector for achieving several of the targets under United Nations Sustainable Development Goal 6 (clean water and sanitation for all) and what policymakers need to do to hit multiple goals with an integrated and coherent policy approach. Since *WEO-2019*, the time horizon is 2050, instead of 2040 as used in previous versions, in order to reflect in our modelling the announcements made by several countries to achieve carbon neutrality by 2050 and also allows us to model the potential for new technologies (such as hydrogen and renewable gases) to be deployed at scale. The interpretation of the climate target embodied in the Sustainable Development Scenario also changes over time, as a consequence of both ongoing emissions of CO_2 as well as developments in climate science (refer to the emissions chapter for more details).

Selected updates for the World Energy Outlook 2021

The following changes were made to the WEM:

Regional scope

- Colombia was shifted to the grouping of advanced economies in Central and South America.
- Guyana is now modelled as an individual country in the oil and gas supply module.

Final energy consumption

Behavioural analysis

- The modelling of behavioural changes and their impacts on energy demand has been updated. Several new specific behavioural changes have been modelled in detail, including energy saving practices at home to reduce wasteful energy usage in appliances, water heating and lighting. In addition, the impacts of behavioural changes in commercial buildings have been modelled for the first time.
- The regional granularity of behavioural changes modelling has been improved to reflect differences in the potential scope, scale and speed of adoption of behavioural changes. Inputs into this modelling include the ability of existing infrastructure to support such changes and differences in geography, climate, urbanisation, social norms and cultural values. For example, regions with high levels of private car use today see a more gradual shift than others towards public transport, shared car use, walking and cycling; air travel is assumed to switch to high-speed rail on existing or potential routes only where trains could offer a similar journey time; and the potential for moderating air conditioning in buildings and vehicles takes into account seasonal effects and humidity.

Buildings module

- The representation of building energy efficiency in new and existing buildings was updated for the Net-Zero by 2050 Roadmap and WEO2021. The new methodology shifts from modelling technologies that individually impact the energy performance of building envelope and instead models envelope packages based on the energy efficiency performance of the package. The change applies to modelling of new and existing residential buildings and allows for the specific modelling of the impact on building energy service demand of retrofits of existing buildings and constructions of new buildings with varying levels of energy efficiency. For existing buildings, different type of retrofits impact the level of service demand. The deployment of different types of retrofits is dependent on their costs and implemented policies in each scenario. The methodology is similar for new buildings, with different type of new building envelope efficiency available for the model to choose from.

- Modelling of the impact of behaviour changes on energy demand and CO_2 emissions was refined, with impacts modelled at the technology and fuel level for all regions within the World Energy Model. The modelling of behavioural impacts has also been updated to include the effects of digitalisation in appliances and lighting. The impacts of moderating set point temperatures have been estimated using a deep learning algorithm applied to time series data of outdoor temperatures and electricity demand.

Industry module

- Industry definition was changed to include blast furnaces and coke ovens within the iron and steel sector, as well as chemical feedstock. As a consequence, total final consumption definition also changed, to include blast furnaces and coke ovens.
- Process emissions assessment and accounting was updated with latest data estimates and cross-validation with the ETP industry model.

Transport module

- Scrappage functions have been applied for capturing in a comprehensive way the car market for each WEM region. These functions have been estimated for each region using historical data. This feature provides the capability to the model for early retirements of car fleet.
- The list of transport fuels has been extended including synthetic fuels (i.e. synthetic gasoline/diesel, synthetic kerosene e.tc.).
- Behavioural changes have been refined and updated. For example, the impact of a universal 100 km/h speed limit on motorways has been assessed based on current national speed limits; the potential to for mode shifting away from car use to active and public transport has been updated considering the density of urban populations and the size of population centres.

Electricity generation

- Hydrogen and ammonia based electricity generation technologies have been added to the model, including the application of different levels of co-firing with natural gas and coal.
- Description of the modelling approach for utility-scale battery storage, including operations, cost and learning assumptions.

Other transformation

- In this year's WEO, in line with the accounting improvement achieved for the Net Zero Emissions by 2050 Special Report, we include **biomass feedstock required to produce modern liquid and gaseous biofuels**, e.g. bioethanol, biodiesel or biomethane. Conversion processes are modelled on a process by process basis, with up-to-date technical and economic parameters provided by the Energy Technology Perspectives model. Elements of biomass trade are also considered to take into account the diverse availability of supply across the world.
  This addition ensures that the model provides a complete picture of total biomass inputs in the energy system. IEA scenarios seeking to meet sustainability goals ensure that the peak level of total primary bioenergy demand – including losses from the conversion of biomass into useful fuels – falls within the lowest estimates of global sustainable bioenergy potential in 2050, namely around 100 exajoules (EJ) (Creutzig et al., 2015), while many other sources posit higher levels of global sustainable feedstock potential around 150-170 EJ (Frank, 2021; Wu, 2019).
- WEO 2021 introduces a module that allocates hydrogen production and trade to meet different potential demand levels reflecting supply costs. The IEA continues to improve the level of detail for the modelling of low-carbon hydrogen, a complex topic that touches upon multiple energy supply sources, energy transformation processes (including power generation, biofuels production and the production of hydrogen-based fuels) and nearly all end-use applications. In policy-driven scenarios, cross-border trade is guided by governments' stated intentions to import or export hydrogen and hydrogen-based fuels. Average infrastructure costs for pipelines, storage, shipping and refuelling are estimated per unit of hydrogen supplied.

Fossil-fuel supply module

- The manner in which conventional natural gas production is distinguished by water depth (onshore, shallow [water depth less than 450 metres], deepwater [between 450-1500 metres] and ultra-deepwater [greater than 1500 metres]) was enhanced.
- The following parameters were reassessed in relation to latest available analysis and data: weighted average cost of capital, investment risk, upstream cost inflation, finding and development unit cost, lifting unit cost, tax rate, and technological improvement.

Investment and financing

- A detailed analysis of the sources of finance was carried out by capital spending (balance sheet and project financing), private and public provider, capital structure (debt and equity sources) and origin of funds (international and domestic).
- An analysis was carried out on the performance and targeting of capital flows against the investment needs of long-term net zero emissions goals.
- Investment projections were expanded to include additional interventions for end-use sectors across buildings, industry and transport, and more detailed modelling of hydrogen-based fuel supply.

Emissions

- Methane emissions assessment was improved. The Methane tracker analysis now integrates direct emissions measurements in addition to the bottom-up estimates. These measures are made by stationary monitors, ground vehicles, or aerial instruments such as satellites, drones, and planes and have been scrutinised to only keep credible sources. The methane emissions were also updated to include an assessment combustion efficiency from flaring activities. This assessment was made utilising flaring design standards, local environmental conditions, regulatory frameworks and regulatory enforcement and age of production.

- For the Net Zero Emissions by 2050 Special Report, Direct Air Carbon Capture, Utilisation, Storage (DAC) technologies were implemented. They consume natural gas, to provide heat to the air separation process, and electricity and allow Carbon Dioxide Removal. Technology parameters (efficiency, costs) and deployment projections are shared with Energy Technology Perspectives model.
- For the Net Zero Emissions by 2050 Special Report, bioenergy supply, land use and agriculture, forestry and other land use (AFOLU) emissions modelling was coupled with the WEM model. The modelling was undertaken by the International Institute for Applied Systems Analysis (IIASA) using their Global Biosphere Management Model (GLOBIOM) to provide data on land use and net emissions impacts of bioenergy demand. Coupling IEA WEM bioenergy demand modelling with the IIASA GLOBIOM model allowed bioenergy demand to be adjusted to ensure demand, and resultant land-use, were in line with the lowest assessed levels of sustainable bioenergy supply and in line with achievement of related Sustainable Development Goals.

Energy access

- A new analysis was conducted on the affordability of basic and extended electricity services for households in Africa and Developing Asia. Using poverty data from Lakner et al. (2021), as well as country electricity prices, we analysed the extent to which poverty could bring about energy affordability if households become unable to afford basic electricity services. We considered two bundles of electricity services: an essential bundle (including mobile phone charging, four lightbulbs, and moderated use of a fan and television), and an extended bundle (including the essential bundle plus one refrigerator, and double use of the fan and the television). The number of people at risk of losing basic electricity services was estimated by combining data on the costs of these bundles in different countries with data on the number of additional households pushed across different poverty lines ($1.90/day, $3.20/day or $5.50/day) as a result of the crisis.

Employment

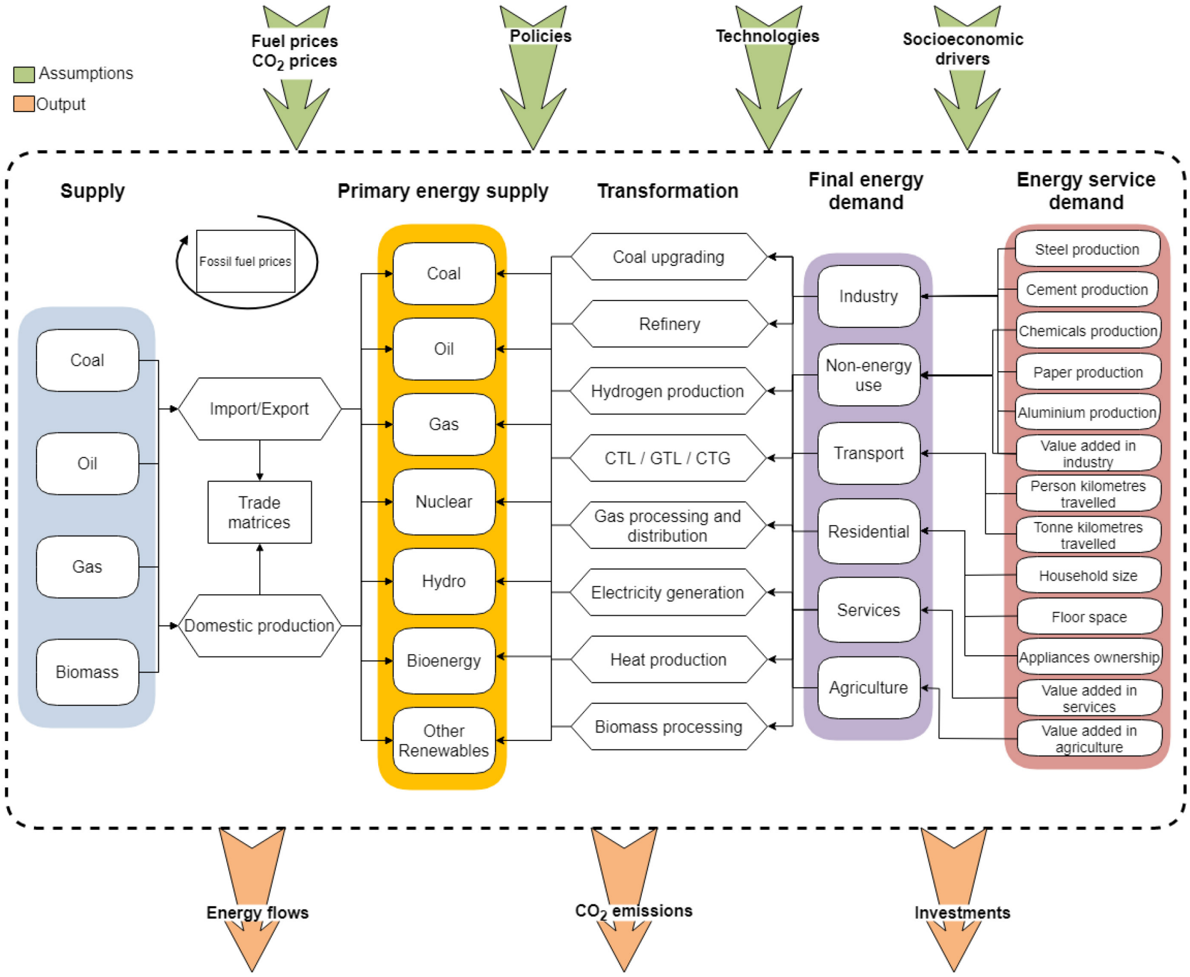
- The model currently analyses the number of people employed in major energy supply and end-use sectors, including electricity, oil, natural gas, coal and biofuels and the number of job losses and gains in the energy and related sectors as a direct product of shifting investments, production, and operation of energy assets. The model estimates how many jobs are created or maintained based on the current asset base and the annual investments in new infrastructure or spending on certain goods or energy commodities.

World Energy Model structure

The WEM is a simulation model covering energy supply, energy transformation and energy demand. The majority of the end-use sectors use stock models to characterise the energy infrastructure. In addition, energy-related CO_2 emissions and investments related to energy developments are specified. Though the general model is built up as a simulation model, specific costs play an important role in determining the share of technologies in satisfying an energy service demand. In different parts of the model, Logit and Weibull functions are used to determine the share of technologies based upon their specific costs. This includes investment costs, operating and maintenance costs, fuel costs and in some cases costs for emitting CO_2. (Figure 1)

The main exogenous assumptions concern economic growth, demographics and technological developments. Electricity consumption and electricity prices dynamically link the final energy demand and transformation sector. Consumption of the main oil products is modelled individually in each end-use sector and the refinery model links the demand for individual products to the different types of oil. Demand for primary energy serves as input for the supply modules. Complete energy balances are compiled at a regional level and the CO_2 emissions of each region are then calculated using derived CO_2 factors. The time resolution of the model is in annual steps over the whole projection horizon. The model is each year recalibrated to the latest available data. The formal base year is 2019, as this is the last year for which a complete picture of energy demand and production is in place. However, we have used more recent data wherever available, and we include 2020 and 2021 estimates for energy production and demand. Estimates are based on updates of the Global Energy Review reports which relies on a number of sources, including the latest monthly data submissions to the IEA's Energy Data Centre, other statistical releases from national administrations, and recent market data from the IEA Market Report Series that cover coal, oil, natural gas, renewables and power.

Figure 1: World Energy Model Overview

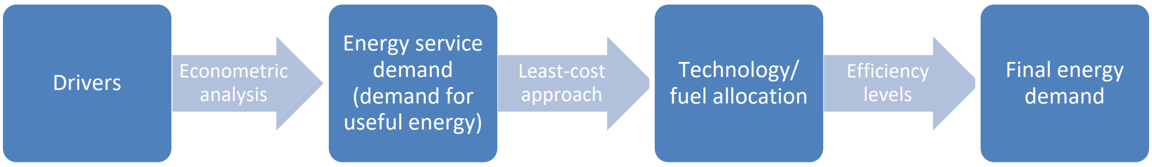


Note: CTL = coal-to-liquids, GTL = gas-to-liquids, CTG = coal-to-liquids.

2 Technical aspects and key assumptions

Demand side drivers, such as steel production in industry or household size in dwellings, are estimated econometrically based on historical data and on socioeconomic drivers. All end-use sector modules base their projections on the existing stock of energy infrastructure. This includes the number of vehicles in transport, production capacity in industry, and floor space area in buildings. The various energy service demands are specifically modelled, in the residential sector *e.g.* into space heating, water heating, cooking, lighting, appliances, space cooling. To take into account expected changes in structure, policy or technology, a wide range of technologies are integrated in the model that can satisfy each specific energy service. Respecting the efficiency level of all end-use technologies gives the final energy demand for each sector and sub-sector (Figure 2). Simulations are carried out on an annual basis. The WEM is implemented in the simulation software Vensim (www.vensim.com), but makes use of a wider range of software tools.

Figure 2: General structure of demand modules



The same macroeconomic and demographic assumptions are used in all the scenarios, unless otherwise specified. The projections are based on the average retail prices of each fuel used in final uses, power generation and other transformation sectors. These end-use prices are derived from projected international prices of fossil fuels and subsidy/tax levels.

Population assumptions

Rates of population growth for each WEM region are based on the medium-fertility variant projections contained in the United Nations Population Division report (UNPD, 2019). In *WEO-2021*, world population is projected to grow by 0.8% per year on average, from 7.7 billion in 2020 to 9.6 billion in 2050. Population growth slows over the projection period, in line with past trends: from 1.3% per year in 2000-2020 to 1.0% in 2020-2030 (Table 2).

Estimates of the rural/urban split for each *WEM* region have been taken from UNPD (2019). This database provides the percentage of population residing in urban areas by country in 5-yearly intervals over the projection horizon. By combining this data[1] with the UN population projections an estimate of the rural/urban split may be calculated. In 2020, about 56% of the world population is estimated to be living in urban areas. This is expected to rise to 68% by 2050.

[1] Rural/Urban percentage split is linearly interpolated between the 5-yearly intervals.

Table 2: Population assumptions by region

	Compound average annual growth rate			Population (million)			Urbanisation (Share of population)		
	2000-20	2020-30	2020-50	2020	2030	2050	2020	2030	2050
North America	1.0%	0.7%	0.5%	496	526	578	82%	84%	89%
United States	0.8%	0.6%	0.5%	330	349	379	83%	85%	89%
C & S America	1.1%	0.8%	0.5%	522	562	603	81%	84%	88%
Brazil	1.0%	0.6%	0.3%	213	224	229	87%	89%	92%
Europe	0.4%	0.0%	0.0%	699	701	690	75%	78%	84%
European Union	0.2%	-0.1%	-0.2%	451	447	429	75%	77%	84%
Africa	2.7%	2.6%	2.2%	1 340	1 688	2 489	43%	48%	59%
Middle East	2.3%	1.7%	1.2%	247	289	348	72%	76%	81%
Eurasia	0.4%	0.3%	0.2%	236	244	253	65%	67%	73%
Russia	-0.1%	-0.2%	-0.2%	144	142	134	75%	77%	83%
Asia Pacific	1.1%	0.7%	0.4%	4 210	4 488	4 727	47%	53%	63%
China	0.6%	0.2%	-0.1%	1 411	1 436	1 375	62%	71%	80%
India	1.4%	1.0%	0.6%	1 380	1 504	1 639	34%	40%	53%
Japan	0.0%	-0.5%	-0.6%	126	120	105	92%	93%	95%
Southeast Asia	1.3%	0.9%	0.6%	667	726	792	50%	56%	66%
World	**1.3%**	**1.0%**	**0.8%**	**7 749**	**8 501**	**9 687**	**56%**	**60%**	**68%**

Notes: C & S America = Central and South America.

Source: IEA *WEO-2021*.

Macroeconomic assumptions

Economic growth assumptions for the short to medium term are are broadly consistent with the latest assessments from the IMF. Over the long term, growth in each WEM region is assumed to converge to an annual long-term rate. This is dependent on demographic and productivity trends, macroeconomic conditions and the pace of technological change.

In WEO-2021, despite the Covid-19 pandemy, the trajectory for economic recovery is relatively rapid, especially in countries that have mobilised strong fiscal support. The global economy is assumed to grow by around 3.0% per year on average over the period to 2050, with large variations by country, by region and over time (Table 3). The assumed rates of economic growth are held constant across the scenarios, which allows for a comparison of the effects of different energy and climate choices against a common backdrop

The way that economic growth plays through into energy demand depends heavily on the structure of any given economy, the balance between different types of industry and services, and on policies in areas such as pricing and energy efficiency.

Table 3: Real GDP average growth assumptions by region and scenario

	Compound average annual growth rate			
	2010-2020	2020-2030	2030-2050	2020-2050
North America	1.6%	2.4%	2.0%	2.1%
United States	1.7%	2.3%	1.9%	2.1%
Central and South America	0.3%	2.8%	2.6%	2.7%
Brazil	0.3%	2.3%	2.7%	2.5%
Europe	1.1%	2.3%	1.5%	1.8%
European Union	0.8%	2.1%	1.3%	1.5%
Africa	2.5%	4.2%	4.2%	4.2%
Middle East	1.7%	2.6%	3.1%	2.9%
Eurasia	1.8%	2.5%	1.6%	1.9%
Russia	1.3%	2.2%	1.1%	1.4%
Asia Pacific	4.7%	4.9%	3.1%	3.7%
China	6.7%	5.2%	2.9%	3.6%
India	5.1%	7.1%	4.4%	5.3%
Japan	0.4%	1.1%	0.7%	0.8%
Southeast Asia	4.2%	4.9%	3.2%	3.8%
World	**2.6%**	**3.6%**	**2.7%**	**3.0%**

Note: Calculated based on GDP expressed in year-2020 US dollars in purchasing power parity terms.

Source: IEA WEO-2021.

Prices

International fossil fuel prices

International prices for coal, natural gas and oil in the WEM reflect the price levels that would be needed to stimulate sufficient investment in supply to meet projected demand. They are one of the fundamental drivers for determining fossil-fuel demand projections in all sectors and are derived through iterative modelling. The supply modules calculate the output of coal, gas and oil that is stimulated under the given price trajectory taking account of the costs of various supply options and the constraints on production rates. In the case that the price is not sufficient to cover global demand, a price feedback is provided into the previous price level and the energy demand is recalculated. The new demand arising from this iterative process is again fed back into the supply modules until the balance between demand and supply is reached in each year of projections. The resulting fossil fuel price trajectories appear smooth, but in reality prices are likely to be more volatile and cyclic.

Fossil fuel price paths vary across the scenarios (Table 4). For example, in the Stated Policies Scenario, although policies are adopted to reduce the use of fossil fuels, demand is still high. That leads to higher prices than in the Sustainable Development Scenario, where the lower energy demand means that limitations on the production of various types of resources are less significant and there is less need to produce fossil fuels from resources higher up the supply cost curve.

The oil price follows a smooth trajectory over the projection horizon. We do not try to anticipate any of the fluctuations that characterise commodity markets in practice, although near-term demand for oil remains robust in the Stated Policies Scenario.

The economic recovery in 2021 has tightened commodity markets and put upward pressure on prices. Some analysts see this as an indicator that the world may be entering a new super cycle, i.e. a prolonged period during which strong demand and some constraints on supply lead to high prices for energy and other commodities.

Table 4: Fossil fuel prices by scenario

			Net Zero by 2050		Sustainable Development		Announced Pledges		Stated Policies	
Real terms (USD 2020)	**2010**	**2020**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
IEA crude oil (USD/barrel)	92	42	36	24	56	50	67	64	77	88
Natural gas (USD/MBtu)										
United States	5.2	2.0	1.9	2.0	1.9	2.0	3.1	2.0	3.6	4.3
European Union	8.8	4.2	3.9	3.6	4.2	4.5	6.5	6.5	7.7	8.3
China	7.9	6.3	5.3	4.7	6.3	6.3	8.5	8.1	8.6	8.9
Japan	13.0	7.9	4.4	4.2	5.4	5.3	7.6	6.8	8.5	8.9
Steam coal (USD/tonne)										
United States	60	43	24	22	24	22	25	25	39	38
European Union	109	50	52	44	58	55	66	56	67	63
Japan	127	69	58	50	67	63	73	63	77	70
Coastal China	137	89	61	51	72	66	77	65	83	74

Notes: MBtu = million British thermal units. The IEA crude oil price is a weighted average import price among IEA member countries. Natural gas prices are weighted averages expressed on a gross calorific-value basis. The US natural gas price reflects the wholesale price prevailing on the domestic market. The European Union and China natural gas prices reflect a balance of pipeline and LNG imports, while the Japan gas price is solely LNG imports. The LNG prices used are those at the customs border, prior to regasification. Steam coal prices are weighted averages adjusted to 6 000 kilocalories per kilogramme. The US steam coal price reflects mine mouth prices plus transport and handling cost. Coastal China steam coal price reflects a balance of imports and domestic sales, while the European Union and Japanese steam coal prices are solely for imports.
Source: IEA *WEO-2021*.

CO_2 prices

CO_2 price assumptions are one of the inputs into WEM as the pricing of CO_2 emissions affects demand for energy by altering the relative costs of using different fuels. Several countries have already today introduced emissions trading schemes in order to price carbon, while many others have schemes under development. Other countries have introduced carbon taxes – taxes on fuels according to their related emissions when combusted – or are considering to do so.

The Stated Policies Scenario takes into consideration all existing or announced carbon pricing schemes, at national and sub-national level. In the Sustainable Development Scenario, it is assumed that CO_2 pricing is established in all advanced economies and that CO_2 prices in these markets start to converge from 2025, reaching $140/tonne CO_2 in most advanced economies in 2040. In addition, several developing economies are assumed to put in place schemes to limit CO_2 emissions. All regional markets have access to offsets, which is expected to lead to a convergence of prices (Table 5).

Table 5: CO_2 prices for electricity, industry and energy production in selected regions by scenario

USD (2020) per tonne of CO_2	2030	2040	2050
Stated Policies			
Canada	55	60	75
Chile, Colombia	15	20	30
China	30	45	55
European Union	65	75	90
Korea	40	65	90
Announced Pledges			
Advanced economies with net zero pledges[1]	120	170	200
China	30	95	160
Emerging market and developing economies with net zero pledges	40	110	160
Sustainable Development[2]			
Other advanced economies	100	140	160
Other selected emerging market and developing economies	-	35	95
Net Zero Emissions by 2050			
Advanced economies	130	205	250
Major emerging economies[3]	90	160	200
Other emerging market and developing economies	15	35	55

Note: The values are rounded.

[1] The CO_2 price for Canada reaches USD 135 per tonne of CO_2 in 2030 as stated in its Healthy Environment and Healthy Economy Plan.

[2] All regions with net zero pledges have the same pricing as in the APS. China's CO_2 pricing rises to the levels of other emerging market and developing economies with net zero pledges in the SDS.

[3] Includes China, Russia, Brazil and South Africa.

Source: IEA WEO-2021.

End-user prices

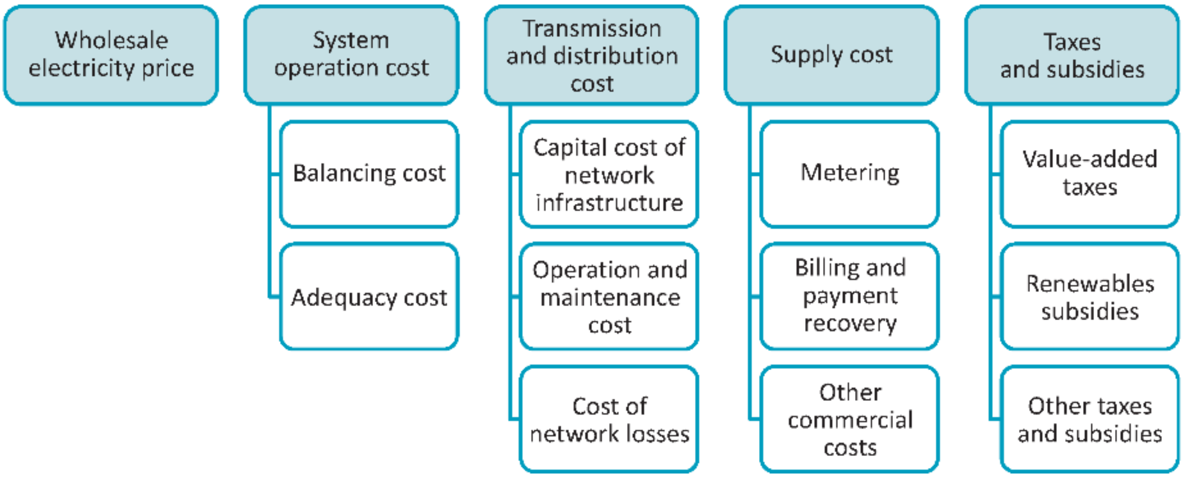
Fuel end-use prices

For each sector and WEM region, a representative price (usually a weighted average) is derived taking into account the product mix in final consumption and differences between countries. International price assumptions are then applied to derive average pre-tax prices for coal, oil, and gas over the projection period. Excise taxes, value added tax rates and subsidies are taken into account in calculating average post-tax prices for all fuels. In all cases, the excise taxes and value added tax rates on fuels are assumed to remain unchanged over the projection period. We assume that energy-related consumption subsidies are gradually reduced over the projection period, though at varying rates across the WEM regions and the scenarios. In the Sustainable Development Scenario, the oil price drops in comparison to the Stated Policies Scenario due to lower demand for oil products. In order to counteract a rebound effect in the transport sector from lower gasoline and diesel prices, a CO_2 tax is introduced in the form of an increase of fuel duty to keep end-user prices at the same level as in the Stated Policies Scenario. All prices are expressed in US dollars per tonne of oil equivalent and assume no change in exchange rates.

Electricity end-use prices

The model calculates electricity end-use prices as a sum of the wholesale electricity price, system operation cost, transmission & distribution costs, supply costs, and taxes and subsidies (Figure 3). Wholesale prices are calculated based on the costs of generation in each region, under the assumption that all plants recover their variable costs and that new additions recover their full costs of generation, including their capital costs. System operation costs are taken from external studies and are increased in the presence of variable renewables in line with the results of these studies. Transmission and distribution tariffs are estimated based on a regulated rate of return on assets, asset depreciation and operating costs. Supply costs are estimated from historic data, and taxes and subsidies are also taken from the most recent historic data, with subsidy phase-out assumptions incorporated over the Outlook period in line with the relevant assumptions for each scenario.

Figure 3: Components of retail electricity end-use prices



There is no single definition of wholesale electricity prices, but in the World Energy Model the wholesale price refers to the average price (across time segments) paid to generators for their output. They reflect the region-specific costs of generating electricity for the marginal power plants in each time segment, plus any capital costs that are not recovered. The key factors affecting wholesale prices are therefore:

- The capital cost of electricity generation plants;
- The operation and maintenance costs of electricity generation plants; and
- The variable fuel and, if applicable, CO_2 cost of generation plants' output.

Wholesale electricity price

The derivation of the wholesale price for any region makes two fundamental assumptions:

- Electricity prices must be high enough to cover the variable costs of all the plants operating in a region in a given year.
- If there are new capacity additions, then prices must be high enough to cover the full costs – fixed costs as well as variable costs – of these new entrants.

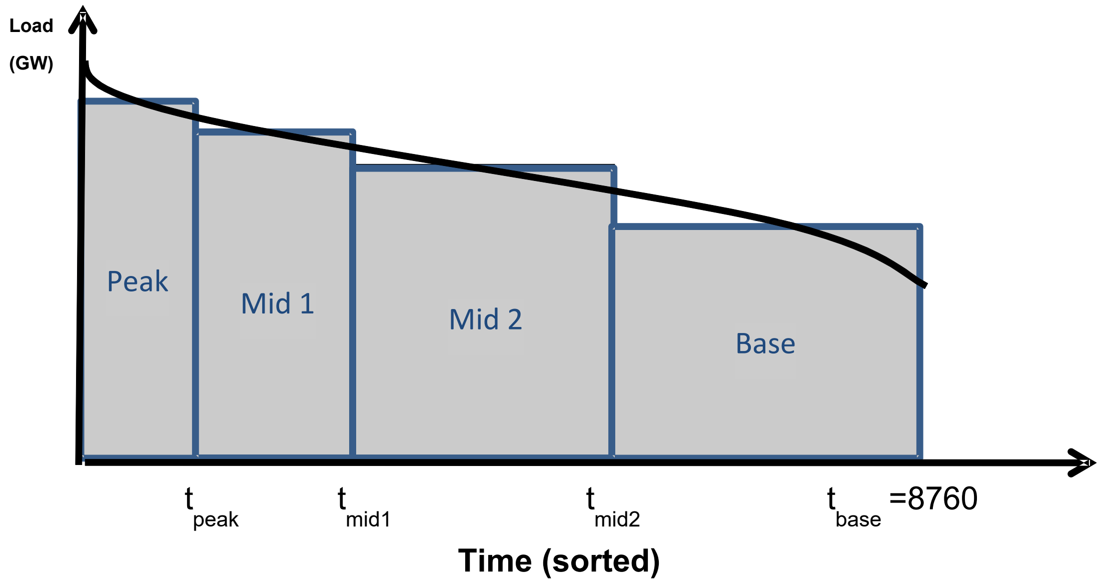
Derivation of a simplified merit order for thermal power plants

For each region, WEM breaks the annual electricity demand volume down into four segments:

- baseload demand, representing demand with a duration of more than 5944 hours per year;
- low-mid load demand, representing demand with a duration of 3128 to 5944 hours per year;
- high-mid load demand, representing demand with a duration of 782 to 3128 hours per year; and
- Peak load demand, representing demand with a duration of less than 782 hours per year.

This results in a simplified four-segment load-duration curve for demand (Figure 4). This demand must be met by the electricity generation capacity of each region, which consists of variable renewables – technologies like wind and solar photovoltaics (PV) without storage whose output is driven by weather – and dispatchable plants (generation technologies that can be made to generate at any time except in cases of technical malfunction). In order to account for the effect of variable renewables on wholesale prices, the model calculates the probable contribution of variable renewables in each segment of the simplified load-duration curve. Subtracting the contribution of renewables from each segment in the merit order leaves a residual load-duration curve that must be met by dispatchable generators.

Figure 4: Load duration curve showing the four demand segments



Calculation of average marginal cost in each merit order segment

Given the variable costs of all the plants in operation in each region, the WEM calculates a merit order of dispatchable plants in each region. This ranks all the plants in order from those with the lowest variable costs to the highest.

It then calculates which types of generator are used during each segment of the residual load-duration curve based on the merit order; i.e. plants with the lowest variable costs are given priority, and plants with the highest variable costs are used only in peak periods.

Once the generation from each plant has been allocated to the four segments of the merit order, the model calculates the marginal variable cost of generation in each segment by looking at average variable cost of the additional plants operating in each segment. For example, for the low-mid load segment of the merit order, the model excludes plants that are also operating in the baseload period and calculates the average variable cost of the remainder. This gives a price for each merit order segment based on the average marginal variable cost of generators operating in that segment.

Given that the model assumes that new entrants must recover their full generation costs in addition to ensuring that all plants recover their variable costs, the model then calculates total revenues to all plants based on the segments in which they operate and the price in each segment. For example, a baseload plant would receive the peak load price for 782 hours of its operation, the high-mid load price for 3128 - 782 = 2346 hours of its operation, the low-mid load price for 5944 - 3128 = 2816 hours and the baseload price for the rest of its operating hours. If there are new entrants, and if the price in any segment is too low to cover their costs, then the price in those segments is increased to the level required to justify new entry.

Calculation of wholesale price based on average marginal cost

Once a price has been calculated in each segment that satisfies the twin requirements of meeting all generators' variable costs and new entrants' full costs, the wholesale price level is then calculated as follows:

$$Wholesale\ price = \frac{\sum_{s=1}^{4}(p_s \cdot d_s \cdot h_s)}{\sum_{s=1}^{4}(d_s \cdot h_s)}$$

where *s* represents the four periods, p_s is the price in each segment (in $/MWh) , d_s is the demand level in each segment (in MW), and h_s is the number of hours in the period (in h). (Note that this results in a volume-weighted wholesale price, rather than a time-weighted price).

Subsidies to fossil fuels

The IEA measures fossil fuel consumption subsidies using a price-gap approach. This compares final end-user prices with reference prices, which correspond to the full cost of supply, or, where appropriate, the international market price, adjusted for the costs of transportation and distribution. The estimates cover subsidies to fossil fuels consumed by end-users and subsidies to fossil-fuel inputs to electricity generation.

The price-gap approach is designed to capture the net effect of all subsidies that reduce final prices below those that would prevail in a competitive market. However, estimates produced using the price-gap approach do not capture all types of interventions known to exist. They, therefore, tend to be understated as a basis for assessing the impact of subsidies on economic efficiency and trade. Despite these limitations, the price-gap approach is a valuable tool for estimating subsidies and for undertaking comparative analysis of subsidy levels across countries to support policy development (Koplow, 2009).

3 Energy demand

All 26 model regions are modelled in considerable sectoral and end-use detail. Specifically:

- Industry is composed of six sub-sectors;
- Buildings energy demand is separated into six end-uses;
- Transport demand is separated into nine modes with considerable detail for road transport.

Total final energy demand is the sum of energy consumption in each final demand sector. In each sub-sector or end-use, at least seven types of energy are shown: coal, oil, gas, electricity, heat, hydrogen and renewables. The main oil products – liquefied petroleum gas (LPG), naphtha, gasoline, kerosene, diesel, heavy fuel oil (HFO) and ethane – are modelled separately for each final sectors.

In most of the equations, energy demand is a function of activity variables, which again are driven by:

- *Socio-economic variables:* In all end-use sectors GDP and population are important drivers of sectoral activity variables.
- *End-user prices:* Historical time-series data for coal, oil, gas, electricity, heat and biomass prices are compiled based on the IEA Energy Prices & Taxes database and several external sources. Average end-user prices are then used as a further explanatory variable — directly or as a lag.

Industry sector

The industrial sector in the WEM is split into six sub-sectors: non-ferrous metals (which includes aluminium), iron and steel, chemical and petrochemical (both energy and feedstock), non-metallic minerals (which includes cement), pulp and paper, and other industry.[2] The iron and steel sub-sector is modelled together with the sub-sectors of blast furnaces, coke ovens and own use of those two in the industry sector.

Energy consumption in the industry sector is driven by the production for specific products in the energy-intensive sectors – aluminium, iron and steel, primary chemicals (ethylene, propylene, aromatics, ammonia and methanol), cement, and pulp and paper – and by value added in industry for the non-specified industry sectors (Figure 5). Production of energy-intensive goods is econometrically projected for a specific year with the help of the following variables: population, end-use energy prices, value added in industry, per capita consumption of the previous year and a time constant. Historic production data is collected from a range of sources, including International Aluminium Institute (*aluminium*), World Steel Association (*steel*), METI and PLATTS (*ethylene, propylene and aromatics*), USGS (*ammonia*, *cement*), RISI and FAO (*paper*).

Since WEO-2019, calculation of industrial products demand and production by region are performed with a tool shared with the Energy Technology Perspectives industry team. Activity variables are therefore perfectly consistent and aligned with the Energy Technology Perspectives scenarios. This tool builds on macroeconomic drivers, such as GDP, population, value added by industry as well as industry parameters such as historical production and production capacities which are under construction, or planned.

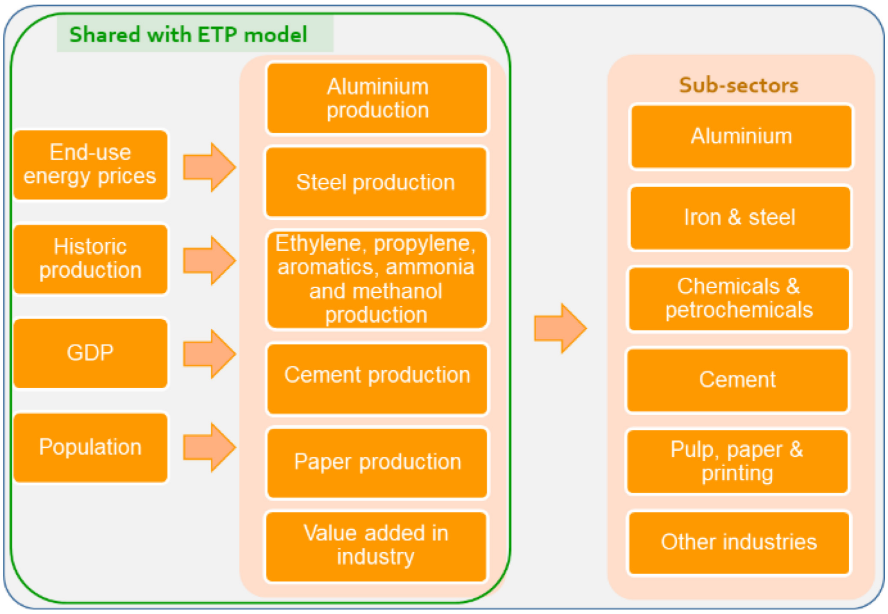
Steel projections of demand and production were overhauled in preparation for the IEA Steel Roadmap 2020. The new methodology explicitly models steel demand based on a per-capita approach reflecting saturation levels of demand. It then derives production of steel on a per-country basis through an international trade module. In *WEO-2020*, a new steelmaking pathway using hydrogen for direct reduced iron production is added to the technology basket. It is an alternative to use of coal and leads to a drastic reduction of CO_2 emissions as long as

[2] Other industry is an aggregate of the following (mainly non-energy intensive) sub-sectors: transport equipment, machinery, mining and quarrying, food and tobacco, wood and wood products, construction, textile and leather, and non-specified.

hydrogen is produced from a low-carbon fuel. Ammonia production projections were comprehensively reviewed for the [Ammonia Technology roadmap 2021](#).

Based on the projected production numbers it is possible to calculate the capacity necessary to satisfy the demand. Furthermore, we estimate current capacity and capacity vintage in each model region, which allows the calculation of retired capacity given our assumptions on average lifetime. This allows us to determine the required capacity additions as the sum of replacing retired capacity and meeting demand increases in a specific year. Major energy efficiency improvements are generally limited in scope for existing industrial infrastructure. This is reflected in our modelling by restricting the adoption of energy-efficient equipment to newly installed capacity. However, we allow for early retirement of existing infrastructure in order to adopt more efficient infrastructure.

Figure 5: Structure of the industry sector



Note: ETP = Energy Technology Perspectives

Final energy consumption in each sub-sector is calculated as the product of production projections and energy intensity of the manufacturing process. While the energy consumption per unit of output is fairly stable for existing infrastructure, the energy intensity of new capacity depends on the adoption of energy-efficient equipment and the level of energy prices.[3]

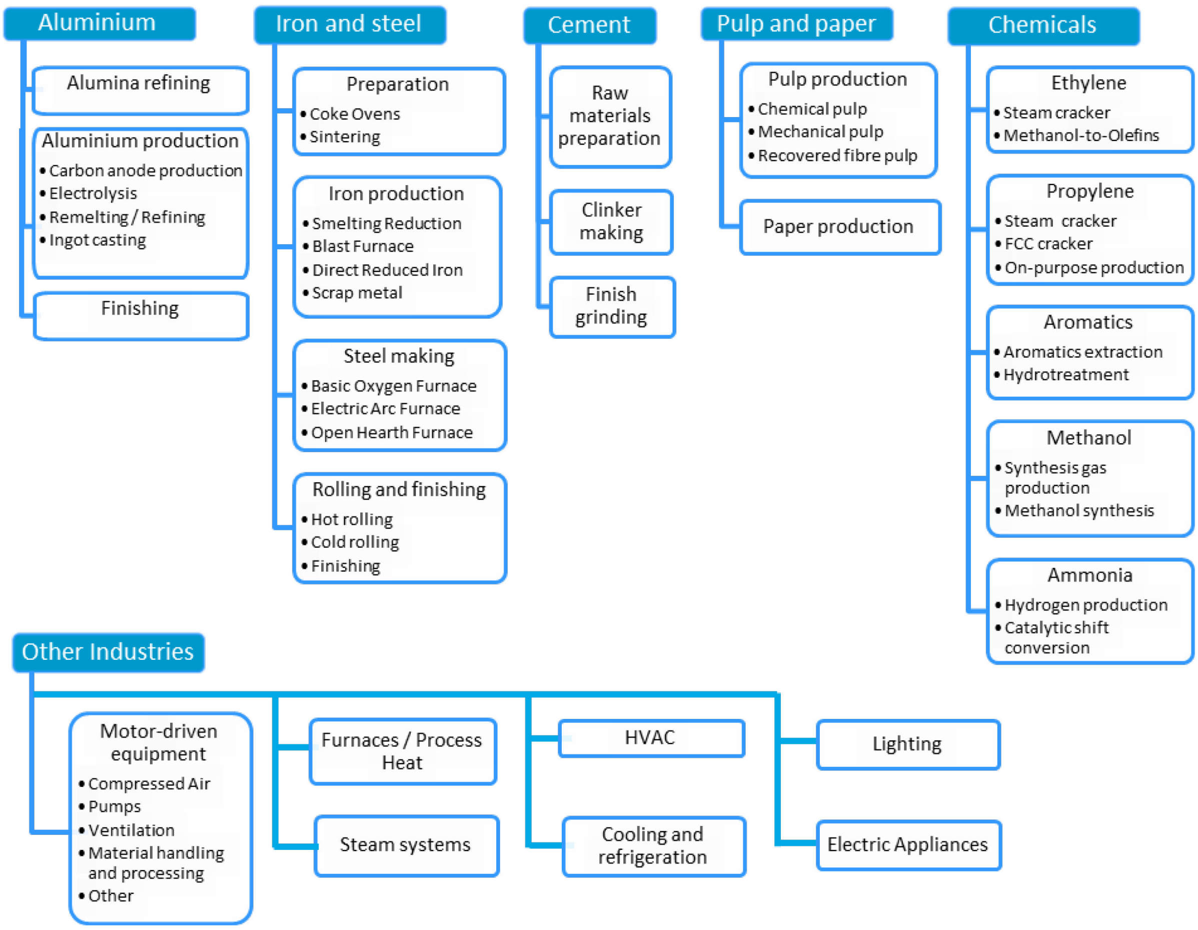
Technological efficiency opportunities are detailed by each industrial process for aluminium, iron and steel, five major product groups in chemicals and petrochemicals, cement, pulp and paper, and cross-cutting technologies in non-energy intensive sectors (Figure 6). Energy-efficient technologies are adopted as a function of their payback period and their potential penetration rate, which varies by scenario. Next to single equipment efficiency, systems optimisation and process changes represent further efficiency options integrated in the industry sector model. Process changes take the form of an increased use of scrap metal in the aluminium industry, increased use of scrap metal, direct reduced iron and electric arc furnaces in the iron and steel industry,

[3] For more details on modelling energy efficiency potentials in industry in *WEO*, see Kesicki and Yanagisawa (2014).

a decreased clinker-to-cement ratio in the cement industry, and an increased use of recycled paper in the pulp and paper industry.

The data on energy-saving technologies is compiled from industry associations, individual companies and range of pertinent literature sources.

Figure 6: Major categories of technologies by end-use sub-sector in industry



Accounting for physical and technological constraints, the share of each energy source is projected on an econometric basis relying on the previous year's share, the fuel price change, the price change in the previous year and a time constant. In this context, electricity is separately modelled from fossil fuels, heat, biomass and waste because there are very limited possibilities to substitute electricity for another fuel or vice versa. However, a potential electrification of the industry sector is taken into account via wider process changes (e.g. increasing the share of electric arc furnaces in steel production). Fuel switches, for example from oil-based products to natural gas, are possible and modelled via a multiple logit model. First, a utility function is defined for each fuel:

$$V_{i,t} = \alpha_i * \frac{price_{i,t}}{price_{fuel\ average,t}} + \beta_{time} * t + \gamma_{adj}$$

$$with\ i = coal, oil, natural\ gas, district\ heat\ and\ biomass$$

where $V_{i,t}$ is the utility function of fuel *i* at year *t*, α_i is a regression coefficient for fuel *i*, $price_{i,t}$ is the fuel price of fuel *i* at year *t* and $price_{fuel\ average,t}$ is the weighted average price of all fuels at time *t*. β_{time} is a time constant (in general, this is set to zero) and γ_{adj} is an adjustment factor that represents non-price influences, such as fuel-specific policies.

In a next step, the choice probability is determined based on the utility function of each fuel:

$$\pi_{i,t} = \frac{exp(V_{i,t})}{\sum_i exp(V_{i,t})}$$

where $\pi_{i,t}$ is the choice probability of fuel *i* at time *t*.

The fuel share is eventually calculated taking into account the fuel share in the previous year and the choice probability:

$$share_{i,t} = share_{i,t-1} + \delta * (\pi_{i,t} - share_{i,t-1})$$

where $share_{i,t}$ stands for the share of fuel *i* in year *t*, and δ is between 0 and 1 and represents the adjustment speed.

Since *WEO-2017*, heat supply capacities and production costs within industry are explicit and new and renewables technologies deployment modelling was integrated into a single framework. This has been done together with adding one temperature dimension to the modelling, in the form five temperature levels (0-60°C, 60-100°C, 100-200°C, 200-400°C and above 400°C), defining potentials in which the different technologies can deploy, depending on their specific costs and performances at each temperature level. Deployment of these technologies is assessed against a counterfactual technology representing the average fossil-fuel-based technology that would otherwise be used that given year, through Weibull functions using the average levelized production costs of the different options and allowing for the calibration of inertia, policies and existing/lack of infrastructure.

Chemicals and petrochemicals sector

The chemicals and petrochemicals sector is characterised by a variety of products that can be produced via different pathways. Furthermore, in this sector, energy is used not only as a fuel but also as a feedstock. In the WEM, we have separately modelled the following intermediate products, which are the most energy-intensive ones to make:

- Organic chemicals
    - Petrochemicals:
        - *Ethylene*
        - *Propylene*
        - *Aromatics* (benzene, toluene and xylenes)
    - *Methanol*
- Inorganic chemicals
    - *Ammonia*

These product groups account for around half of total fuel consumption and for the vast majority of feedstock consumption. Products that make up the rest of petrochemical and chemical feedstock consumption are butadiene, butylene and carbon black. The distinction between fuel use and feedstock use is important as energy used as feedstock cannot be reduced through efficiency measures.

In order to analyse the energy consumption for these five major intermediate products, the following principal production routes have been implemented in the model:

- Steam cracking (for the production of ethylene, propylene and aromatics)
- Refinery streams (for the production of propylene from fluid catalytic cracking and aromatics from catalytic reforming)
- Propane dehydrogenation (for the production of propylene)

- Methanol-to-olefins (for the production of ethylene and propylene)
- Coal/biomass gasification and natural gas steam reforming (for the production of synthesis gas)
- Methanol synthesis (for the production of methanol from synthesis gas)
- Ammonia synthesis (for the production of ammonia from synthesis gas)

Since the specific energy consumption in steam cracking depends on the oil product being used, inputs into this process are divided into: ethane, liquid petroleum gas, naphtha and heavy fuel oil. As for the other sub-sectors, future production volumes are based on an econometric projection, but in addition the projection takes account of feedbacks from oil supply and the refinery modules to account for the availability of feedstock.

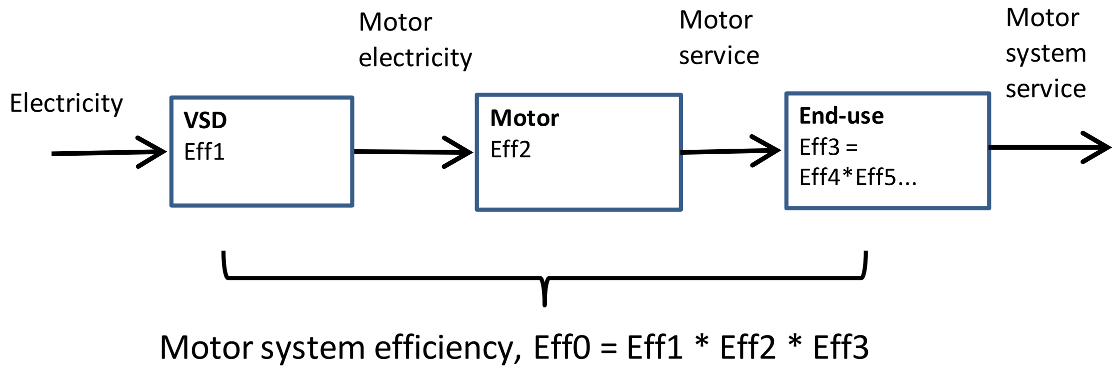
For *WEO-2018,* the updated WEM Industry module includes the possibility to use hydrogen as direct fuel or as feedstock for ammonia production. Intensities and efficiencies of related processes are aligned with assumptions used for the Energy Technology Perspectives report (IEA, 2017c). For ammonia, the used hydrogen does not appear in the balance, as it is only an intermediate product. Only the electricity consumed in the electrolysis, synthesis and in the air-separation processes appear in the balance. For *WEO-2020*, this feature has been extended to methanol production.

Chemical sector models have been updated for *WEO-2018* as a result of work feeding into the Future of Petrochemicals report. Data sources for historic production of chemical products have been updated, along with the feedstock intensities, in both cases with the goal of better aligning with the Energy Technology Perspectives report (IEA, 2017c). The sectoral boundaries for propylene and aromatics have been updated, moving refinery production out of the chemicals sector energy/feedstock demand and including better representation of energy demand for steam crackers.

Motor efficiency

A sub-model for industrial electric motors (illustrated in Figure 7) was is part of WEM since *WEO-2016*. The driver for the model is the motor system service demand. This is driven by the projected value-added in the industry sector and can be thought of as the demand for motor system service. The model then has several steps to control efficiencies of three separate modules (being the end-use, the motor and a variable speed drive [VSD]). The efficiencies of these three steps multiplied with each other give the motor system efficiency, Eff0. Dividing the motor system service by Eff0 gives the electricity consumed in industrial electric motor systems.

Figure 7: Structure of the electric motor model



The end-use efficiency is calculated as a weighted average of efficiencies in four end-uses: pumps, fans, mechanical movement and compressors. For each of these four end-uses there is a stock model (with starting year 1980) with efficiencies of each vintage of normal and "efficient" devices. The share of sales of efficient devices is determined by the payback periods of such an investment, controlled by a Gompertz function. The end-use module includes the efficiency of a throttle, which represents the fact that in many motor systems, the outflow is controlled by with a throttle or a damper, thereby bringing the system efficiency down.

Material efficiency

Beyond energy efficiency technologies and measures, the WEM industry model can also represent material efficiency strategies, enabling further energy savings. Given the large share of energy costs in production costs in energy-intensive sectors, the potentials to increase energy efficiency are in general more limited compared with less energy-intensive industries. Possible material efficiency strategies to limit the growth of these sectors' energy consumption are:

- Re-use materials: Use of post-consumer scrap directly (i.e. without re-melting) for the same or other applications.
- More efficient production: Reduce the losses in the product process by increasing manufacturing and semi-manufacturing yield rates.
- Light-weighting products: Produce the same product with a lower average mass per product.
- Increase recycling: Increase collection rates of post-consumer scrap.
- Divert fabrication scrap: Instead of remelting fabrication scrap, it can be used for other applications.
- More intensive use of products: Use material-intensive goods more intensively, e.g. by sharing a car or using a building for a higher share of the day.
- Longer life times: Extend the life time of material components in products.

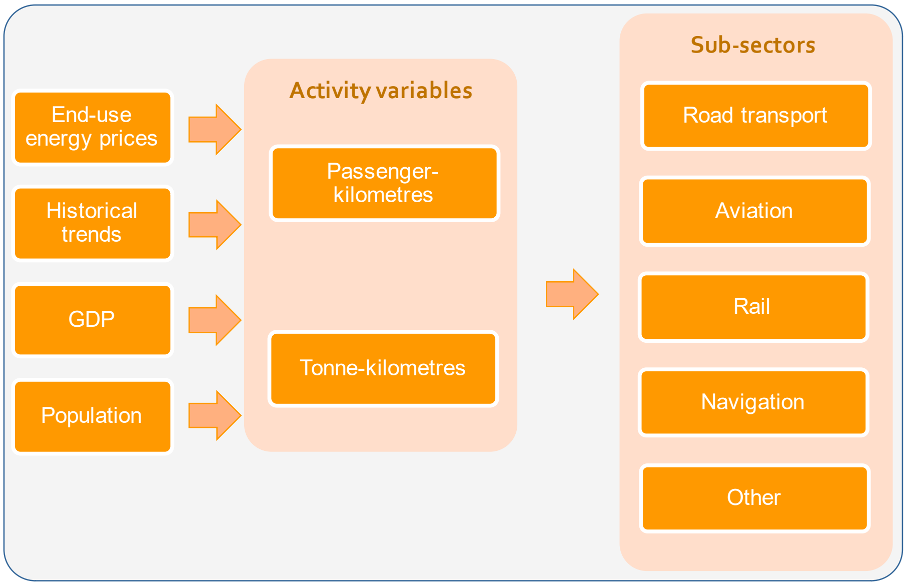
For this purpose, material flow models for aluminium and steel demand enable realistic assumptions for these material efficiency strategies to be incorporated into the model, helping the assessment of future demand and the amount of scrap metal (semi-manufacturing, manufacturing and post-consumer scrap) available for metals production. This modelling work builds mainly on the literature and previous IEA publications relating to material efficiency (IEA 2019a). The scope of this approach is limited to materials and energy demand within the respective industry sectors. It does not analyse the implications on energy consumption upstream, in mining or the transportation of materials, nor the consequences for downstream energy consumption, e.g. from more efficient, lighter cars. Nor does the study analyse the potential for energy savings from substituting materials, e.g. using plastics for metals.

Transport sector

The transportation module of the WEM consists of several sub-models covering road, aviation, rail and navigation transport modes (Figure 8). The WEM fully incorporates a detailed bottom-up approach for the transport sector in all WEM regions.

For each region, activity levels such as passenger-kilometres and tonne-kilometres are estimated econometrically for each mode of transport as a function of population, GDP and end-user price. Transport activity is linked to price through elasticity of fuel cost per kilometre, which is estimated for all modes except passenger buses and trains and inland navigation. This elasticity variable accounts for the "rebound" effect of increased car use that follows improved fuel efficiency. Energy intensity is projected by transport mode, taking into account changes in energy efficiency and fuel prices. The road module is calibrated to historical fuel use, i.e. the gasoline, diesel, natural gas and electricity, which is updated every year and ensure that the model reflects closely on recent developments in terms of vehicle stocks, vehicle mileages and vehicle efficiencies. A gap factor is used to account for differences between test cycle fuel consumption and on-road fuel use.

Figure 8: Structure of the transport sector



Note: 'Other' includes pipeline and non-specified transport.

Road transport

Road transport energy demand is broken down among passenger light duty vehicles (PLDVs), light commercial vehicles (LCVs), buses, medium trucks, heavy trucks and two- and three-wheelers. The model allows fuel substitution and alternative powertrains across all sub-sectors of road transport. The gap between test and on-road fuel efficiency, i.e. the difference between test cycle and real-life conditions, is also estimated and projected.

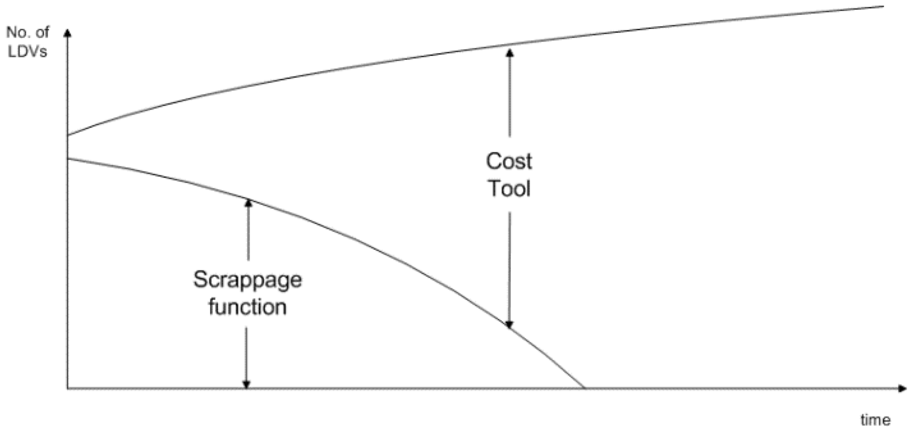
As the largest share of energy demand in transport comes from oil use for road transport, the WEM contains technology-detailed sub-models of the total vehicle stock and the passenger car fleet. In its origin, the stock projection model is based on an S-shaped Gompertz function, proposed in Dargay et al. (2006). This model gives the vehicle ownership based on income (derived from GDP assumptions) and 2 variables: the saturation level (assumed to be the maximum vehicle ownership of a country/region) and the speed at which the saturation level is reached. The equation used is:

$$V_t = y\, e^{ae^{bGDP_t}}$$

where V is the vehicle ownership (expressed as number of vehicles per 1,000 people), y is the saturation level (expressed as number of vehicles per 1,000 people), a and b are negative parameters defining the shape of the function (i.e. the speed of reaching saturation). The saturation level is based on several country/region specific factors such as population density, urbanisation and infrastructure development. Passenger car ownership is then calculated based on the detailed vehicle fleet data in the IEA Mobility Model (MoMo) plus other regional statistics. Using the equation above, changes in passenger car ownership over time are modelled, based on the average current global passenger car ownership. Both total vehicle stock and passenger vehicle stock projections are then derived based on our population assumptions. Projected vehicle stocks and corresponding vehicle sales are then benchmarked against actual annual vehicle sales and projected road infrastructure developments. The resulting vehicle stock projections can therefore differ from those that would be derived by the use of the Gompertz function alone.

The analysis of **passenger light-duty vehicle (PLDV)** uses a cost tool that guides the choice of drivetrain technologies and fuels as a result of their cost-competitiveness. The tool acts on new passenger-LDV sales as depicted in Figure 9, and determines the share of each individual technology in new passenger LDVs sold in any given year.

Figure 9: The role of passenger-LDV cost model



The purpose of the cost tool is to guide the analysis of long-term technology choices using their cost-competitiveness as one important criterion. The tool uses a logit function for estimating future drivetrain choices in passenger LDV.[4] The share of each PLDV type *j* allocated to the passenger light duty vehicle market is given by

$$Share_j = \frac{b_j P_{PLDV_j}^{r_p}}{\sum_j \left(b_j P_{PLDV_j}^{r_p} \right)}$$

where

- P_{PLDVj} is the annual cost of a vehicle, including annualised investment and operation and maintenance costs as well as fuel use
- r_p is the cost exponent that determines the rate at which a PLDV will enter the market
- b_j is the base year share or weight of $PLDV_j$

The cost database in the cost tool builds on an analysis of the current and future technology costs of different drivetrains and fuel options, comprising the following technology options:

- conventional internal combustion engine (ICE) vehicles (spark and compression ignition)
- hybrid vehicles (spark and compression ignition)
- plug-in hybrids (spark and compression ignition)
- electric cars with different drive ranges
- hydrogen fuel cell vehicles

The model takes into account the costs of short- and long-term efficiency improvements in personal transport distinguishing numerous options for engine (e.g. reduced engine friction, the starter/alternator, or transmission improvements) and non-engine measures (e.g. tyres, aerodynamics, downsizing, light-weighting or lighting). In addition, it uses projections for the costs of key technologies such as batteries (NiMH and Li-ion) and fuel cells. The pace of technology cost reductions is then calculated using learning curves at technology-specific learning rates.

[4] Originally developed to describe the growth of populations and autocatalytic chemical reactions, logit functions can be applied to analyse the stock turnover in different sectors of the energy system. Here, it uses the cost-competitiveness of technology options as an indicator for the pace of growth.

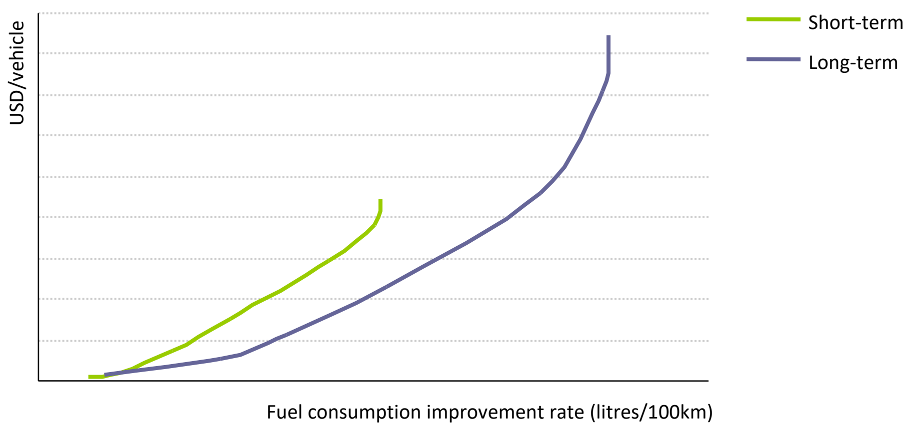
The cost analysis builds on a comprehensive and detailed review of technology options for reducing fuel consumption. The database was reviewed by a panel of selected peer-reviewers, and feeds into the cost tool. The cost database is constantly reviewed and takes account of recent research. This year, the cost curves assumptions across all vehicle types were updated based on JRC work (Krause et al, 2017; Krause and Donati, 2018). Regional characteristics and economic factors have been taken into account in order to expand cost curves coverage for all WEM regions.

For the purpose of electric cars projections, a thorough review on electromobility targets for the top 20 global automakers has been conducted. This analysis permits us to assess if the automakers commitments for launching new electrified car models are falling behind the necessary EVs rollout for meeting fuel economy goals and Zero Emission Vehicles mandates. Automakers with ICEs phase out commitments are also part of this analysis.

Regarding hydrogen vehicles projections, they take into account the recent car market developments, policy announcements and the key outcomes from IEA's hydrogen report (IEA, 2019c).

Road freight transport vehicles can be broadly classified into light-commercial vehicles (<3.5t), trucks (3.5t – 16t) and heavy trucks (>16t). For the latter two categories, WEM comprises two detailed sub-models to guide the development of average fuel economy improvements on the one hand, and technology choices on the other hand. For the former, the model endogenises the decision of investments in energy efficiency by taking the view of rationale economic agents on the basis that minimising costs is a key criterion for any investment decision in this sector. Using the efficiency cost curves of NRC, the model calculates the undiscounted payback period of an investment into more fuel-efficient trucks and heavy trucks. The model then allows for investments where the calculated payback period is shorter than an assumed minimum payback period that is required by fleet operators (generally assumed between 1 and 3 years, depending on the region). The problem is solved in an iterative manner as the model seeks to deploy the next efficiency step on the efficiency cost curve as determined by literature, but may use efficiency improvement levels in between individual steps on the efficiency cost curve. An example of an efficiency cost curve is depicted in Figure 10.

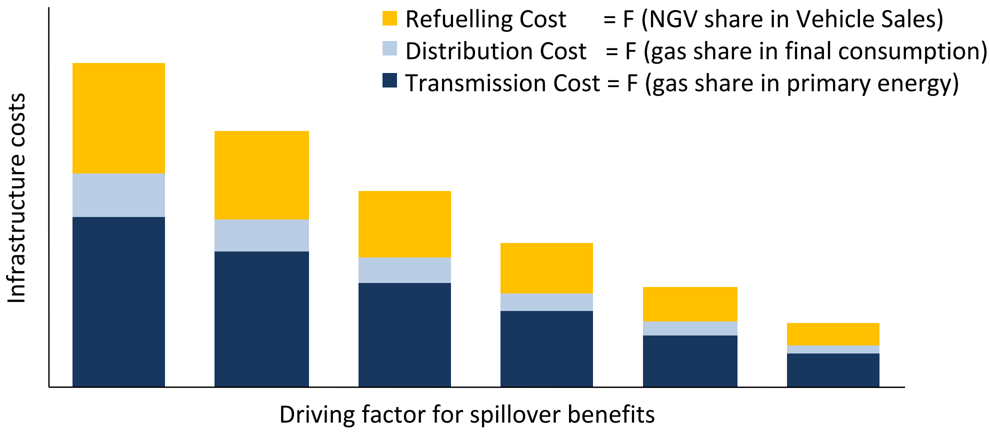
Figure 10: Illustration of an Efficiency Cost Curve for Road Freight



In a second step, the model simulates the cost effectiveness of a conventional internal combustion engine vehicle against other competing options such as hybrid vehicles and natural gas vehicles. The simulation is guided by the use of a Weibull function. Alternative powertrains for medium- and heavy-duty trucks have been implemented in the WEM: fuel cell, battery electric and plug-in hybrid electric.

In order to assess the problems created due to chicken-and-egg-type of situations when it comes to the deployment of those alternative fuels in transport that require a dedicated refuelling infrastructure, and to better reflect potential spill-over effects of the use of such alternative fuels in other sectors of the energy system, the WEM has two dedicated sub-models, one covering natural gas infrastructure and the other electricity-related refuelling infrastructure. In principle, both modules seek to quantify the costs and benefits of increased infrastructure availability for transmission and distribution of these alternative fuels. Thus, in the case of natural gas, an enhanced share of natural gas use in primary energy demand (for example in the power generation sector) would lead to the development of a transmission grid in the economy; and similarly, an increased share of natural gas in final energy consumption by end use sectors (for example, in industry or buildings) will lead to an expanded distribution grid close to the consumption centres, thereby impacting the overall availability of natural gas in the economy and simultaneously driving down the transmission and distribution costs for all consumers, including the transportation sector. Moreover, an increased share of natural gas vehicles (NGVs) in total vehicle sales in the region would gradually improve the development and utilization of a refuelling network due to increased density of vehicles served per station, thereby reducing the average cost of refuelling. This relationship is thus implemented as a positively reinforcing loop, wherein increased penetration of natural gas (in all other sectors, not just transport) and natural gas vehicles helps driving down the overall refuelling infrastructure costs. In essence, the relationship of these spill-over benefits can be illustrated as in Figure 11.

Figure 11: Refuelling infrastructure cost curve (illustrative)



For the case of electric vehicles, availability of transmission and distribution grid is less of an issue, especially in OECD countries, thanks to the already existing widespread use of electricity in different end use sectors (especially buildings). However, the availability of electric recharging infrastructure is one of the important constraints in this case, and hence it is important to determine how a reduction in refuelling costs could influence the possibility for oil substitution in road transport. Therefore, the electric vehicle (EV) sub-module assesses the cascading effect of an increased share of electric vehicles in overall vehicle sales on bringing down the refuelling costs. Detailed cost curves were prepared outlining the reduction of refuelling costs with the increase in overall vehicle stock of electric vehicles. These cost curves were provided as an exogenous input to the model, so as to continuously adjust the refuelling costs as the share of EV sales rises in the future.

Finally, based on projections of the average fuel consumption of new vehicles by vehicle type, the road transport model calculates average sales and stock consumption levels (on-road and testcycle) and average emission levels (in grammes of CO_2 per kilometre) over the projection period. It further determines incremental investment costs relative to other scenarios and calculates implicit CO_2 prices that guide optimal allocation of abatement in transport.

Aviation

Aviation is among the fastest growing transport sectors. The aviation model is updated in collaboration with the IEA's Energy Technology Perspectives team which maintains the Mobility Model (MoMo). The model aims at assessing air traffic measured in revenue passenger kilometres (RPKs) and for passenger travel and revenue tonne-kilometres (RTK) for cargo. RPKs refer to the number of passengers which generate revenue multiplied by the kilometres they fly. RTKs refer to the number of tonnes carried which generate revenue multiplied by the kilometres they are flown. A detailed review of publically available historical data for the aviation sector was conducted to update the historical database of WEM and MoMo. It includes data from the International Civil Aviation Organization, aircraft manufacturers such as Airbus, Boeing and Embraer, and the Japan Aircraft Development Corporation. As a result, RPKs were estimated at 8.6 trillion in 2019, while RTKs were at over 1 trillion (ICAO, 2019).

Future RPK and RTK growth is guided by projections of various factors, using growth in per capita income by region as a main driver:

- the number of flights per year and capita by model region, which grows as a function of population and income growth ;
- the average flight distances by model region, which gradually declines on a global level in line with recent trends (although with differences by model region); and
- the average flight occupancy, which is assumed to remain constant at current levels.

To assess future fuel consumption as a result of RPK and RTK growth, the model projects the resulting fuel intensity that global fuel consumption growth complies with an annual average fuel efficiency improvement of RPK growth of 2% per year from 2020 to 2050, as expressed by the Assembly of the International Civil Aviation Organization (ICAO). A further sub-model calculates investment costs and marginal abatement costs split by the types of abatement measure.

Maritime

In collaboration with the IEA's Energy Technology Perspectives team, which maintains the IEA Mobility Model, a specific approach is implemented in the WEM since *WEO-2016*. The aim of this overhaul was to have a better understanding of maritime freight demand from a bottom-up perspective, which is driven by projections of maritime trade. In the previous approach, we regarded energy demand for international maritime transport from a top-down perspective driven by growth in GDP PPP. The new bottom-up structure is based on the ASIF (Activity, Structure, Intensity and Fuel use) framework (Schipper, 2010) to assess energy demand and CO_2 emissions by region and ship type.

The activity variable represents the maritime trade demand in tonne-kilometre, i.e. tonnes carried multiplied by number of kilometres they are shipped. It covers global physical flows of maritime trade of 19 commodity types, by origin-destination points between 26 regions. Physical and monetary trade numbers and projections (2010-2050) were derived from the International Transport Forum freight model (Martinez et al., 2014) and revised to reflect changes in value to weight ratios of energy products. The data were aggregated to account for five ship types (oil tankers, bulk carriers, general cargo, container ships and others). The structure variable is interpreted as the load factor, i.e. the average capacity utilization per ship per trip, which allows deriving the vehicle-kilometres projected for each region and for each ship type. Load factor projections are based on historically observed growth rates of the average size of the different ship types, which are published by UNCTAD. The capacity utilization factor is kept constant. Furthermore, the base year energy intensity values are derived from the IMO 3rd GHG study (IMO, 2014). In the Stated Policies Scenario, projections of the energy intensity variable take into account the effect of Energy Efficiency Design Index (EEDI), introduced by the International Maritime

Organisation (IMO). The EEDI mandates a minimum 10% improvement in the energy efficiency per tonne-km of new ship designs from 2015, 20% from 2020 and 30% from 2025 to 2030. These improvements are benchmarked against the average efficiency of ships built between 1999 and 2009. In the Sustainable Development Scenario, energy efficiency improvements are assumed to converge towards the maximum efficiency improvement potentials, which were assessed for each type of ship. Lastly, combining the activity, structure and energy intensity variable determines the final energy consumption by region and by ship type. Multiplying this number with the CO_2 emission factors of the different fuels modelled (heavy fuel oil, marine diesel oil, LNG and biodiesel) gives the total CO_2 emissions.

Behaviour change analysis

Severally analysis regarding behaviour change in transport have been carried out:

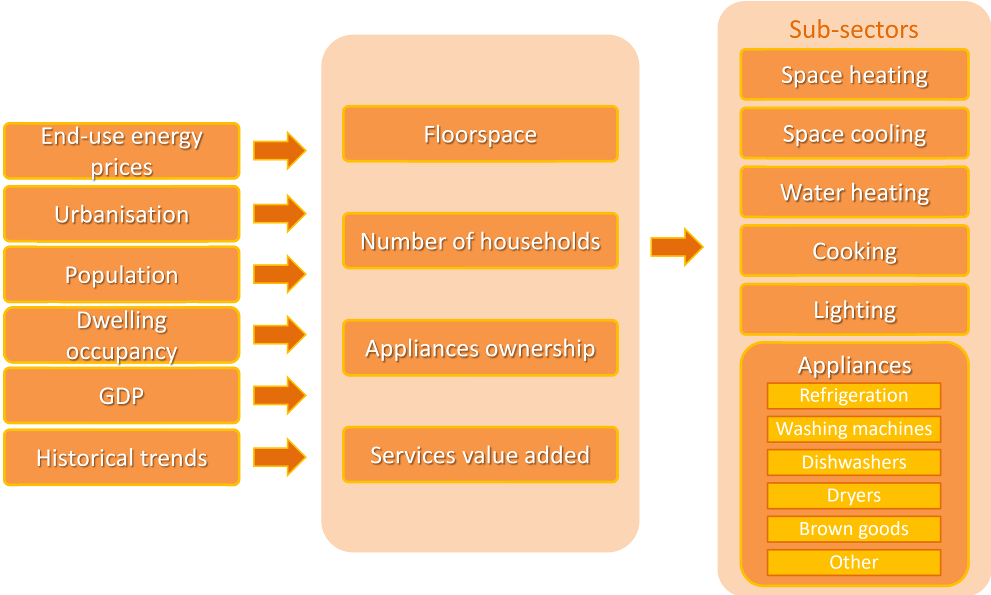
- Ex-post analysis for the impact of behaviour change on aviation sector has been developed. Historical data (OAG, AIM from UCL) has been used to disaggregate aviation activity per person and distance. Changes in occupancy factors have been assumed to assess the impact of behaviour change in oil demand.
- In WEO 2019, an in-depth analysis was performed on the rise of SUVs at a country level. Both commercial (IHS Markit, Jato Dynamics) and in-house (GFEI, MoMo Database) dataset have been used. These analysis have been updated and extended to 2020, using the Marklines database. A moderate growth of SUVs is anticipated in the STEPS.
- The car market in 2021 was analysed using multiple sources (Marklines, EV Volumes etc.), estimating car sales recovery pattern. In WEO 2021, we estimated how much of car sales drop in 2020 came from delayed new purchases and how much from delayed replacement, based on WEM results. Econometric functions have been applied to project the future trend, assuming that the car market will return to normal by 2030.
- Historical data show a shift from public transport to private vehicles due to health concerns. Publicly available reports (i.e. survey by Ipsos) were used to estimate the mobility needs that have to be covered either by bicycles or private cars. Different assumptions have been made for different WEM regions, depending on the accessibility to bikes (i.e. low accessibility in the United States, high accessibility in the Netherlands), and the impact on oil demand due to this modal shift was estimated.
- Regarding the analysis on the impact of teleworking, a literature review on the distance of a commute by mode for key WEM regions has been carried out. These data have been expanded to all regions and the oil demand for each mode have been estimated. After assuming the maximum potential of teleworking of the workforce (i.e. 20% by 2030), the impact of teleworking on oil demand was assessed.

Buildings sector

The buildings sector module of the WEM is subdivided into the residential and services sectors, both having a similar structure (Figure 12). Population, GDP and dwelling occupancy drive the activity variables, such as floor space, appliance ownership, number of households (residential sector) and value added (in the services sector).

In the residential and services sectors, energy demand is further subdivided into six standard end uses in buildings, namely space and water heating, appliances (divided into four different categories: refrigeration – fridge and freezer; cleaning – washing, drying machines and dish washers; brown goods – TVs and computers; and other appliances), lighting, cooking and space cooling. These sub-modules project final energy consumption from the base year over the projection horizon in three steps.

Figure 12: **Structure of the buildings sector**



In a first step, the demand for an energy service, *i.e.* the useful energy demand, is determined, based on the activity variables.

$$End\ use\ service\ demand = Activity\ variable * intensity$$

Here, activity refers to the main driver of the energy service demand – for the residential sector it is floor space area, people per household, and appliances ownership; and for services, it is valued added by the service sector. Intensity refers to the amount of energy service (e.g. space heating) needed per unit of activity variable (e.g. floor space). The activity variables are projected econometrically, based on historical data and linking to socio-economic drivers such as GDP and population. For each end use, the intensity variable is projected using the historical intensity and adjusting, for each projection year, to the change in average end-user fuel prices (using price elasticity) and change in average per capita income (using income elasticity).

In the specific case of space heating and cooling, the intensity projections are also adjusted for historical variations in temperature. Historical energy demand for space heating/space cooling and historical Heating Degree Day (HDD)/Cooling Degree Day (CDD) data is combined to normalise projections of space heating/space cooling energy demand, removing the impact of year on year volatility in energy service needs. The impact of climate change on space heating and cooling demand is included as well. Based on the anticipated change in heating and cooling degree days due to climate change in each region and under each scenario's temperature pathway, the increase in heating and cooling demand is quantified.

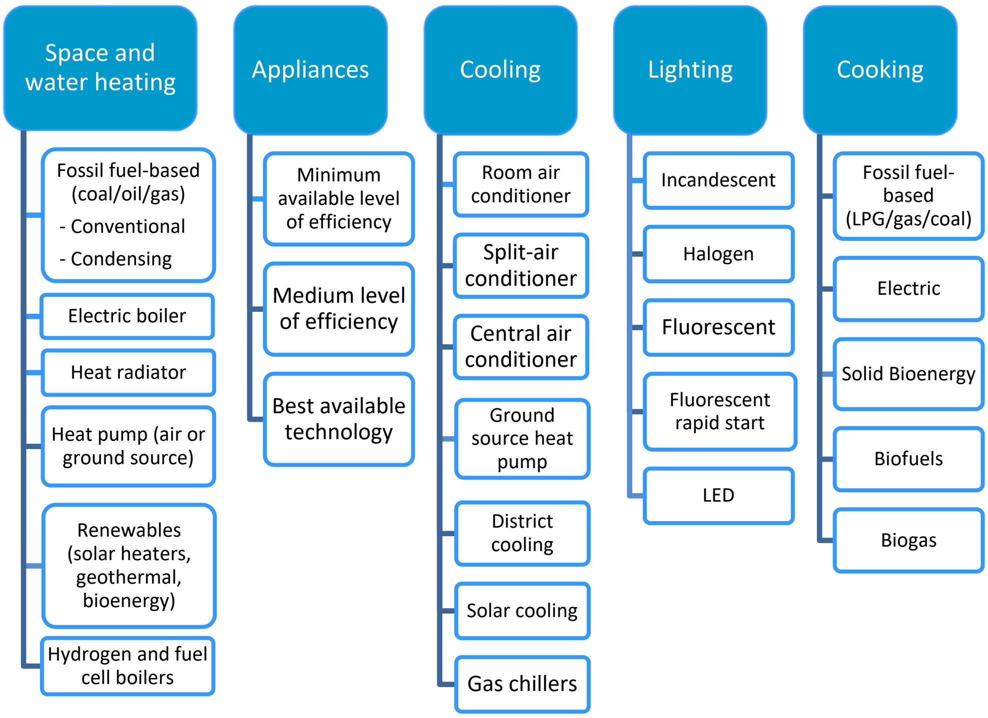
These projections are based on IEA own analysis derived from NCAR GIS Program (2012). Climate Change Scenarios, June 2004, version 3.0. was used to derive data products. For this analysis, outcomes from RCPs 2.6 and 4.5 (anomalies, multi-year mean of monthly data of future climate simulations) have been associated to the SDS and STEPS scenario respectively (see also this commentary https://www.iea.org/commentaries/is-cooling-the-future-of-heating).

The space heating and cooling service demand is computed for existing buildings and new buildings. For existing buildings, the evolution of service demand depends on the share of the building stock that is retrofit and the type of retrofit. The impact of retrofits on energy service demand per square meter varies according to the type of retrofit and the region. The most stringent retrofits allow existing building envelopes to become zero-carbon-ready. The projections of the shares of each type of retrofit depend on their costs and implemented policies in each scenario. The methodology is similar for new buildings, different types of building envelopes can be implemented to lower the service demand. The most efficient envelope corresponds to a zero-carbon ready building. In addition to the impact of the envelope efficiency at the time of building construction, new buildings can subsequently be retrofit in the model. Improvements in the performance of the building envelope (either via more efficient new constructions or via retrofits) reduce the total energy service demand for space heating and space cooling that remains to be met by heating or cooling equipment.

Multiplying the activity by the intensity gives the total end-use service demand (useful energy consumed). Thus, the incremental energy service demand from year to year could be an outcome of increased demand for service (largely in the case of emerging market and developing economies, where demand is still evolving), or the retirement of old units according to equipment retirement rates (as is the case in a majority of advanced economies). Both result in a need for new equipment.

In a second step, the technologies to supply the end-use service demand are chosen. For each end use, there is a detailed set of technologies available to the model (Figure 13). Within each technology option, for example a gas boiler, there are several types, representing the varying levels of efficiency and the associated investment cost. Additionally, there is a possibility to switch fuels and technologies, whereby heat-pumps could be used for space heating, instead of gas boilers. Within the residential sector, additional detail regarding bioenergy allows for more accurate modelling of the historical and projected use of biogas digesters to meet home energy needs, as well as the use of bioethanol and other liquids in cooking stoves and household heating equipment.

Figure 13: Major categories of technologies by end-use subsector in buildings



The technology choice is made based on relative costs, efficiencies of the technologies and policy constraints, if any. The share of technologies is allocated by a Weibull function based on their specific costs per unit of service demand supplied, which includes investment costs, operating and maintenance costs, and fuel costs. The routine allocates the different technologies to satisfy the new service demand for every year over the *Outlook* period. This allocation is subject to upper and lower boundaries, reflecting real-world constraints such as technology availability and adoption, policies, and market barriers.

To assess equipment and appliance efficiency, and related costs, we consulted with a large number of companies, experts and research institutions at the national and international levels. We also conducted an extensive literature review to catalogue technologies that are now used in different parts of the world and to judge their probable evolution (Anandarajah, *et al.*, 2011; Econoler, *et al.*, 2011; IEA, 2010; IEA, 2011; IEA, 2012b; Kannan, *et al.*, 2007; Waide, 2011; IEA, 2013a; IEA2014b). The efficiency potential for electrical appliances has been determined using the BUENAS (Bottom-Up Energy Analysis System) model, an international appliance policy model developed by Lawrence Berkeley National Laboratory (LBNL). BUENAS covers thirteen economies that together account for 77% of global energy consumption, and twelve different end-uses, including air conditioning, lighting, refrigerators and industrial motors (LBNL, 2012). The assessment of efficiency potential in the services sector buildings also benefitted from preliminary estimates available from GBPN (Global Buildings Performance Network) and CEU (Central European University) study on buildings (GBPN and CEU, 2012). The technology database is also now shared with the ETP model.

In a third step, total final energy consumption in the residential and service sector is obtained based on the efficiencies of existing and new building equipment. Efficiency represents the amount of energy needed to meet a unit of service demand, and thus represents the technical performance of the equipment or appliances. Final energy consumption in the buildings sector is a summation of the sub-sectoral energy consumed by the total technology stock, which includes the historical (declining) stock of appliances and equipment, and the new technologies added every year over the *Outlook* period by the technology allocation routine.

$$Final\ energy\ consumption = \frac{1}{\eta} * End\ use\ service\ demand$$

At the same time, investments in all technology additions, as well as envelopes and retrofits are calculated. Carbon emissions related to the buildings sector are also calculated.

The buildings module is directly linked to the access (electricity access and clean cooking access) module to take into account the growth of electricity and of alternative fuels or stoves for cooking (see Section 0).

Behaviour change

Regarding behavioural changes in the residential sector such as lower indoor air temperature settings, lower use of air conditioning, use of line-drying and cool washing, a literature review was carried out to assess the impact on energy consumption. Assumptions regarding the potential allowed us to assess the total impact and the resulting decrease in CO_2 emissions.

Regarding the analysis on the impact of teleworking, a literature review on the impact of working for home on the increase in residential consumption for key WEM regions has been carried out. These data have been expanded to all regions and the total increase for each fuel has been estimated. After assuming the maximum potential of teleworking of the workforce (i.e. 20% by 2030), the impact of teleworking on residential consumption was assessed.

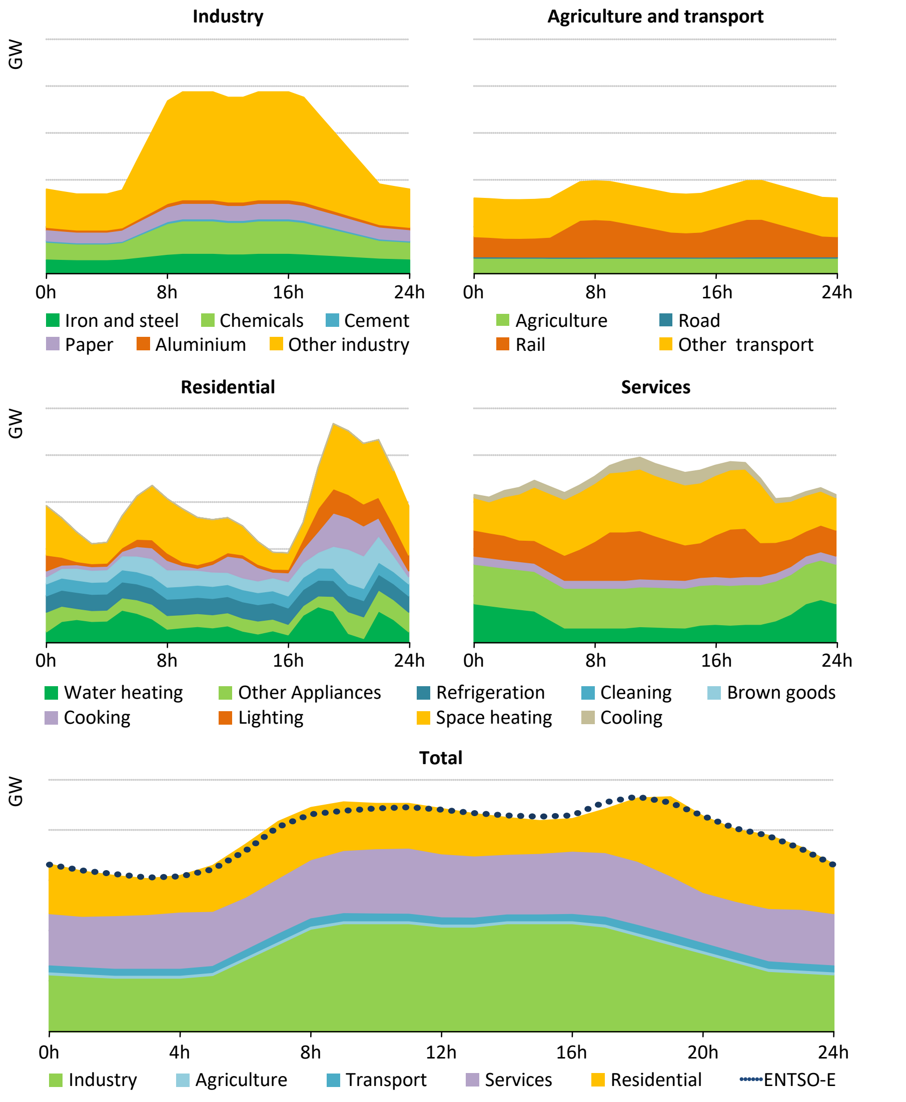
Hourly electricity demand and demand-side response

Understanding the hourly, daily and seasonal evolution of electricity demand is critical to accurate modelling of electricity systems, including assessing electricity system flexibility needs and the role of demand-side response.

Modelling of hourly electricity demand is undertaken at an end-use level. End-use level modelling allows the model to reflect the impact of the full scope of demand side integration measures: electrification and energy efficiency impact the annual demand for end-uses while demand-side response, including load shifting and shedding, impacts demand at a more temporally granular level. Modelling hourly load requires assessment of the hourly load profile for each end-use within each sector, residential and services (e.g. space heating, water heating.), industry (e.g. steel, chemicals industry), transport (e.g. road and rail) and agriculture. Hourly load curves are assessed for every 24 hours of 36 typical days (a weekday, Saturday and Sunday of each month).

Hourly load curves for end-uses are informed by research and survey data where available. In addition, for WEO2021 further detail to its modelling of hourly heating, cooling and lighting electricity demand across the year was added, with deep learning algorithms used to predict space heating and cooling demand for both residential and services buildings based on temperature, building occupancy rates and historical demand. Lighting hourly electricity demand was projected based on building activity and occupation rates, daylight times and insolation levels. The aggregate electricity demand of each end-use or subsector is then matched to the total historical hourly load profile of a given country.[5] An example of the load aggregation is displayed in **Error! Reference source not found.**.

Figure 14: Illustrative load curves by sector for a weekday in February in the European Union compared to the observed load curve by ENTSO-E for 2014



[5] Data from ENTSO-E, PJM, ERCOT, MISO, NEISO, NYISO were used to replicate respectively the overall load curves of European Union, United States and India.

Note: ENTSO-E represents the aggregated load curve for the 28 European Union countries. Sources: (ENTSO-E, 2016); IEA analysis.

Modelling the role and potential of demand-side response requires assessment of the share of demand that is flexible in each end-use. This share is the product of three flexibility factors, sheddability, controllability and acceptability (Ookie Ma, 2013):

- Sheddability: Share of the load of each end-use that can be shed, shifted or increased by a typical DSR strategy.
- Controllability: Share of the load of each end-use which is associated with equipment that has the necessary communications and controls in place to trigger and achieve load sheds/shifts.
- Acceptability: Share of the load for a given end-use which is associated with equipment or services where the user is willing to accept the reduced level of service in a demand-response event in exchange for financial incentives.

This framework enables scenarios to consider demand flexibility from various technologies and at varying levels of social acceptability.

4 Power generation and heat plants

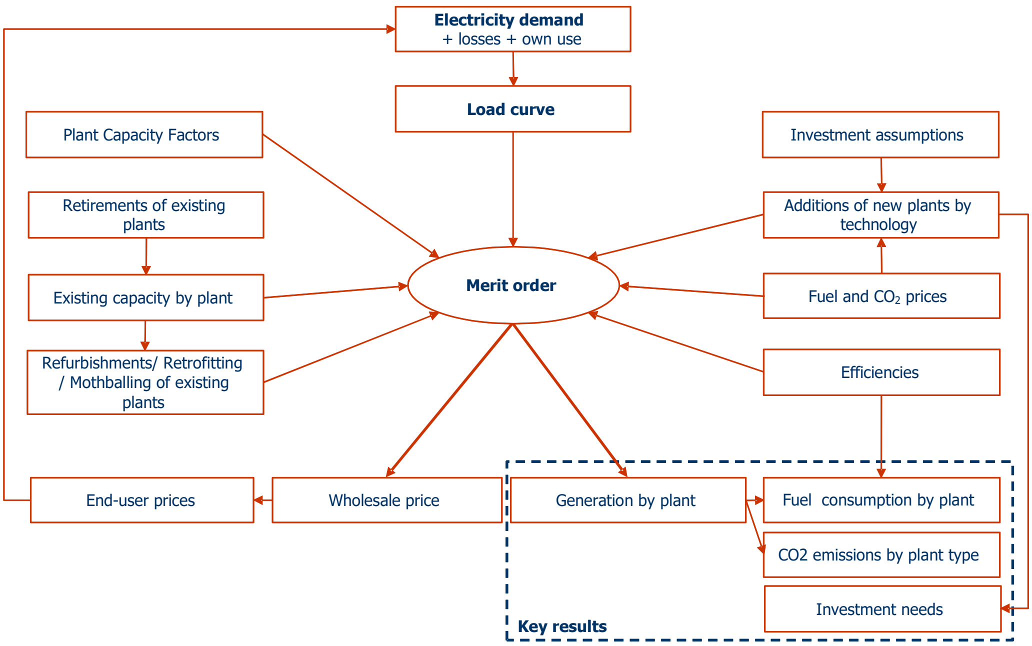
Based on electricity demand, which is computed in all demand sectors (described in section 3), the power generation module calculates the following:

- Amount of new generating capacity needed to meet demand growth and cover retirements and maintain security of supply.
- Type of new plants to be built by technology.
- Amount of electricity generated by each type of plant to meet electricity demand, cover transmission and distribution losses and own use.
- Fuel consumption of the power generation sector.
- Transmission and distribution network infrastructure needed to meet new demand and replace retiring network assets.
- Wholesale and end-use electricity prices.
- Investment associated with new generation assets and network infrastructure.

Electricity generation

The structure of the power generation module is outlined in Figure 15. The purpose of the module is to ensure that enough electrical energy is generated to meet the annual volume of demand in each region, and that there is enough generating capacity in each region to meet the peak electrical demand, while ensuring security of supply to cover unforeseen outages.

Figure 15: Structure of the power generation module



The model begins with existing capacity in each region, which is based on a database of all world power plants. The technical lifetimes of power plants are assumed to range between 45 and 60 years for existing fossil-fuel plants and nuclear plants (unless otherwise specified by government policies). The lifetimes of wind and solar PV installations are assumed to have a distribution centred around 25 years, ranging from 20 to 30 years; hydropower projects 50 years; and bioenergy power plants 25 years.

Capacity additions

The model determines how much new generation capacity is required annually in each region by considering the change in peak demand compared to the previous year, retirements of generation capacity during the year, and any increase in renewable capacity built as the result of government policy. Installed generating capacity must exceed peak demand by a security-of-supply margin; if this margin is not respected after changes in demand, retirements, and renewables additions, then the model adds new capacity in the region. In making this calculation, the model takes into account losses in transmission and distribution networks and electricity used by generation plants themselves.

Because of the stochastic nature of the output of variable renewables such as wind and solar PV, only a proportion of the installed capacity of these technologies can be considered to contribute to the available generation margin. This is reflected in the modelling by the use of a capacity credit for variable renewables. This capacity credit is estimated from historical data on hourly demand and hourly generation from variable renewables in a number of electricity markets, and it reflects the proportion of their installed capacity that can reliably be expected to be generating at the time of peak demand.

When new plants are needed, the model makes its choice between different technology options on the basis of their regional value-adjusted levelised cost of electricity (VALCOE), which are based on the levelised cost of electricity (LCOE), also referred to as the long-run marginal cost (LRMC). The LRMC of each technology is the average cost of each unit of electricity produced over the lifetime of a plant, and is calculated as a sum of levelised capital costs, fixed operation and maintenance (O&M) costs, and variable operating costs. Variable operating costs are in turn calculated from the fuel cost (including a CO_2 price where relevant) and plant efficiency. Our regional assumptions for capital costs are taken from our own survey of industry views and project costs, together with estimates from NEA/IEA (2010). The weighted average cost of capital (pre-tax in real terms) is assumed to be 8% in the OECD and 7% in non-OECD countries unless otherwise specified, for example with revenue support policies, onshore wind and utility-scale solar PV at 3-6% (see financing costs section below), and offshore wind at 4-7% depending on the region.

The LRMC calculated for any plant is partly determined by their utilisation rates. The model takes into account the fact that plants will have different utilisation rates because of the variation in demand over time, and that different types of plants are competitive at different utilisation rates. (For example, coal and nuclear tend to be most competitive at high utilisation rates, while gas and oil plants are most competitive at lower utilisation rates).

The specific numerical assumptions made on capital costs, fixed O&M costs, and efficiency can be found on the WEO website: https://www.iea.org/reports/world-energy-model/techno-economic-inputs.

The levelised cost module computes LRMCs (or LCOEs) for the following types of plant:

- Coal, oil and gas steam boilers with and without CCUS (carbon capture, utilisation and storage);
- Combined-cycle gas turbine (CCGT) with and without CCUS;
- Open-cycle gas turbine (OCGT);
- Integrated gasification combined cycle (IGCC);
- Oil and gas internal combustion;
- Fuel cells;
- Bioenergy with and without CCUS;
- Geothermal;
- Wind onshore;
- Wind offshore;
- Hydropower (conventional);

- Solar photovoltaics;
- Concentrating solar power; and
- Marine
- Utility-scale battery storage

Regional LRMCs are also calculated for nuclear power but additions of nuclear power capacity are subject to government policies.

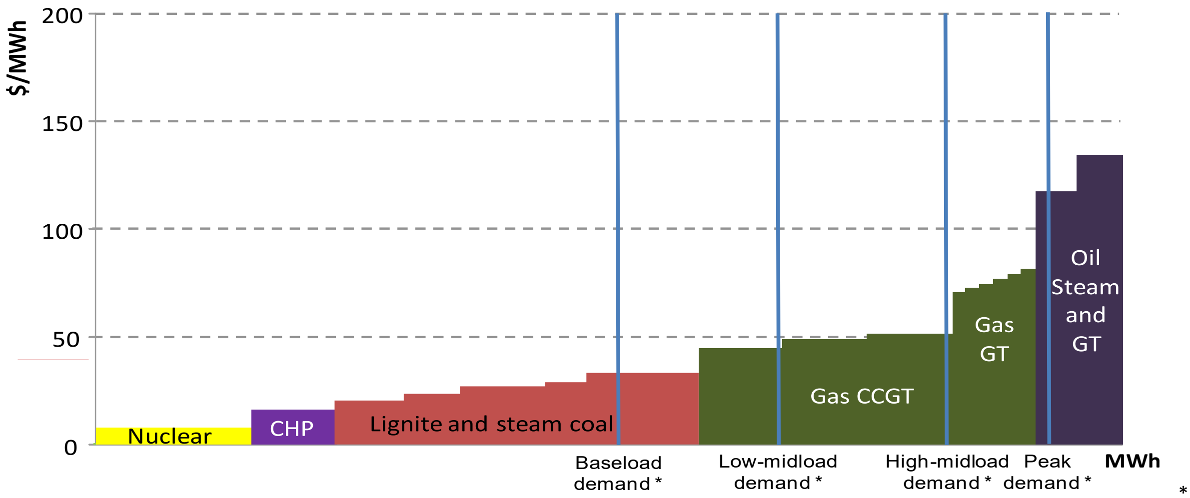
Generation volumes

For each region, the model determines the generation from each plant based on the capacity installed and the level of electricity demand. Demand is represented as four segments:

- baseload demand, representing demand with a duration of more than 5944 hours per year;
- low-midload demand, representing demand with a duration of 3128 to 5944 hours per year;
- high-midload demand, representing demand with a duration of 782 to 3128 hours per year; and
- peakload demand, representing demand with a duration of less than 782 hours per year.

The model subtracts from the demand in each segment any generation coming from plants that must run – such as some CHP plants and desalination plants – and also generation from renewables. For generation from variable renewables, the amount of generation in each demand segment is estimated based on the historical correlation between generation and demand. The remainder of the demand in each segment must be met by production from dispatchable plants. The model determines the mix of dispatchable generation by constructing a merit order of the plants installed – the cumulative installed generation capacity arranged in order of their variable generation costs – and finding the point in the merit order that corresponds to the level of demand in each segment (Figure 16). As a result, plants with low variable generation costs – such as nuclear and lignite-burning plants in the Figure 16 example – will tend to operate for a high number of hours each year because even baseload demand is higher than their position in the merit order. On the other hand, some plants with high variable costs, such as oil-fired plants, will operate only during the peak demand segment.

Figure 16: Example merit order and its intersection with demand in the power generation module



* Demand here means demand net of generation by "must run" plants such as desalination and some CHP plants, and net of generation by renewables.

Calculation of the capacity credit and capacity factor of variable renewables

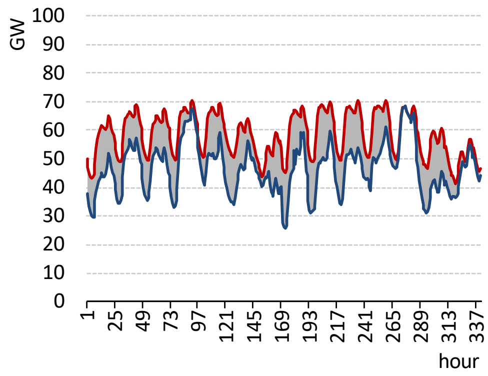
Power generation from weather-dependent renewables such as wind and solar power varies over time and the characteristics of the power supply from variable renewables have to be taken into account for the decisions on dispatch and capacity additions of the remaining, mostly dispatchable power plants. The effect of all variable renewables (solar PV, solar CSP without storage and wind on- and offshore) is taken into account via the capacity credit and the capacity factor in each load segment.

The capacity credit of variable renewables reflects the proportion of their installed capacity that can reliably be expected to be generating at the time of high demand in each segment. It determines by how much non-variable capacity is needed in each load segment. The capacity factor gives the amount of energy produced by variable renewables in each load segment and determines how much non-variable generation is needed in each segment.

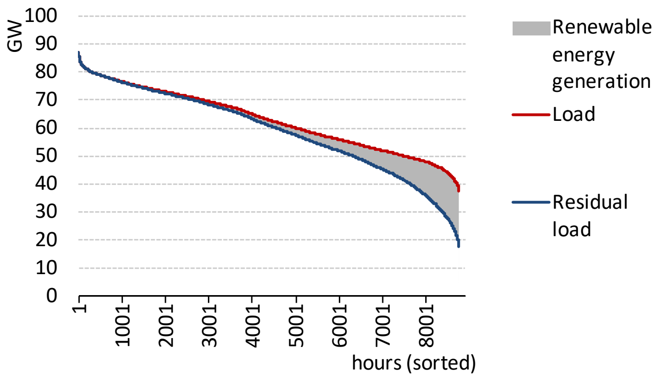
Both, capacity credit and capacity factor are calculated based the comparison between the hourly load profile and the wind and solar supply time-series, derived from meteorological data. To quantify the effects of variable renewables, the hourly load profile is compare to the hourly residual load, being the electricity load after accounting for power generation from variable renewables (see Figure 17a). By sorting the residual load, the levels of average and maximal demand per load segment can be determined. The difference between the load levels of the normal load and the residual load gives the impact of variable renewables on the power generation and capacity needs (see Figure 17b).

Figure 17: Example electricity demand and residual load

a) Load and residual load for selected days



b) Load and residual load duration curve for one year



The capacity factor of variable renewables (varRE) per load segment can be calculated generation per load segment *s* of the residual load.

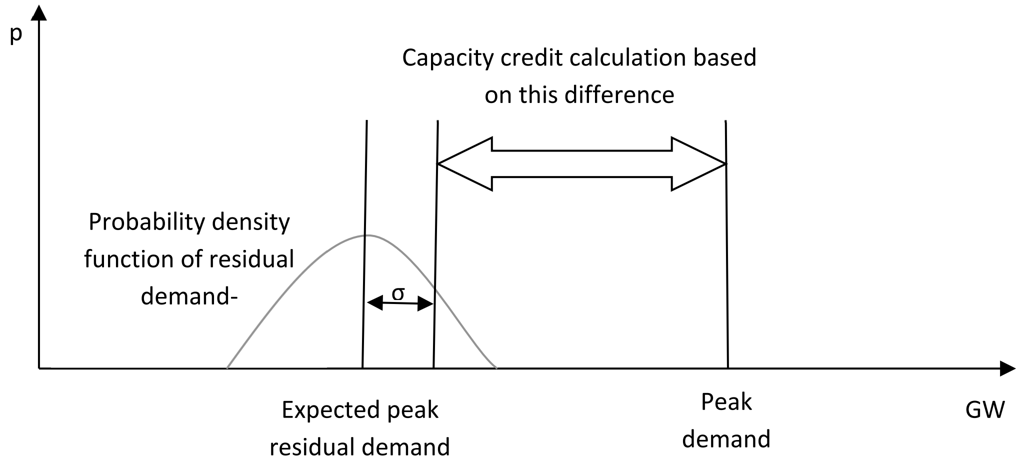
$$Capacity\ factor_s = \frac{Reduction\ Generation\ Needs_{non-var,s}}{Capacity_{varRE}} = \frac{\text{Generation varRE}_s}{Capacity_{varRE}}$$

For capacity additions, the peak load segment is relevant. The capacity credit is estimated based on the difference between maximal load and maximal residual load:

$$Capacity\ credit_{peak} = \frac{Reduction\ Capacity\ Needs_{non-var}}{Capacity_{varRE}} = \frac{\max_t\big(Load(t)\big) - \max_t\big(Residual\ Load(t)\big)}{Capacity_{varRE}}$$

Meteorological data (wind speed and solar irradiation) for several years was used for the capacity credit calculation. In aggregating the results of capacity credit obtained from different years of meteorological data, as first order approach it was assumed that the annual peak residual demand is normally-distributed and calculated the capacity credit based on the difference between peak demand and the point one standard deviation above the residual peak demand (Figure 18).

Figure 18: Exemplary electricity demand and residual load



The meteorological data wind and solar data stems from the following re-analysis datasets

- World Wind Atlas (Sander + Partner GmbH): Global dataset of hourly wind speeds at 10 m height, 1979-2009, derived from reanalysis data based on climate modelling (Suraniana, 2010)
- Wind supply time-series for West and Eastern US as derived by WWITS (2010) and EWITS (2011).
- Wind and solar supply time-series for Europe-27 as provided by Siemens AG (Heide, 2010) for each major Region in Europe. Original meteorological wind speed stems from Reanalysis data (WEBROG, 2008).
- Hourly solar irradiation data from satellite observations for the US (NREL,2010)
- Estimation of solar irradiation based on solar height (Aboumahboub, 2010)

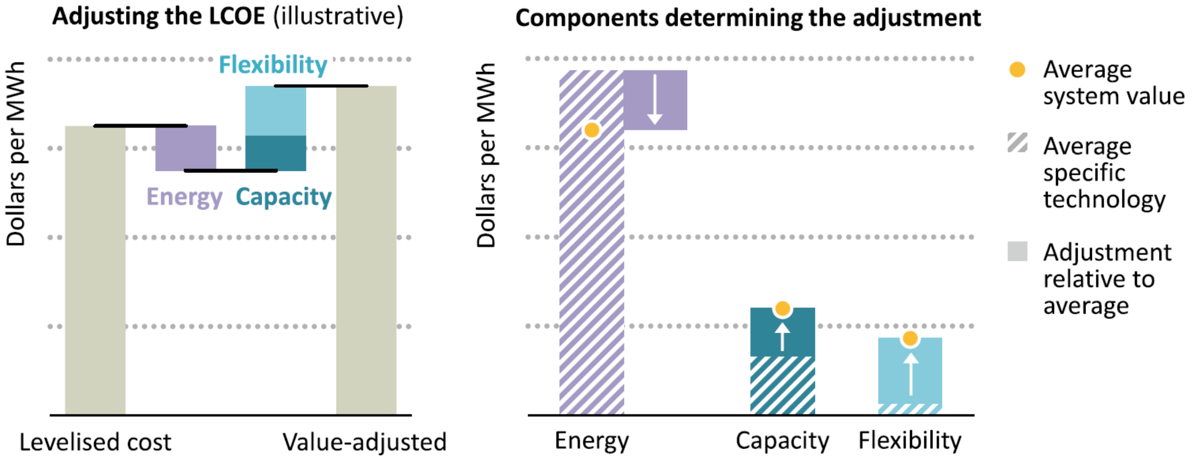
Value-adjusted Levelized Cost of Electricity

Major contributors to the Levelized Cost of Electricity (LCOE) include overnight capital costs; capacity factor that describes the average output over the year relative to the maximum rated capacity (typical values provided); the cost of fuel inputs; plus operation and maintenance. Economic lifetime assumptions are 25 years for solar PV, onshore and offshore wind. For all technologies, a standard weighted average cost of capital was assumed (7-8% based on the stage of economic development, in real terms). Details are in **Error! Reference source not found.**.

The value-adjusted LCOE (VALCOE) is a metric for competitiveness for power generation technologies and was presented for the first time in *WEO-2018*, building on the capabilities of the WEM hourly power supply model. It is intended to complement the LCOE, which only captures relevant information on costs and does not reflect the differing value propositions of technologies. While LCOE has the advantage of compressing all the direct technology costs into a single metric which is easy to understand, it nevertheless has significant shortcomings: it lacks representation of value or indirect costs to the system and it is particularly poor for comparing technologies that operate differently (e.g. variable renewables and dispatchable technologies). VALCOE enables comparisons that take account of both cost and value to be made between variable renewables and dispatchable thermal technologies.

The VALCOE builds on the foundation of the average LCOE (or LRMC) by technology, adding three elements of value: energy, capacity and flexibility. For each technology, the estimated value elements are compared against the system average in order to calculate the adjustment (either up or down) to the LCOE. After adjustments are applied to all technologies, the VALCOE then provides a basis for evaluating competitiveness, with the technology that has the lowest number being the most competitive (Figure 19). The VALCOE is applicable in all systems, as energy, capacity and flexibility services are provided and necessary in all systems, even though they may not be remunerated individually. In this way, it takes the perspective of policy makers and planners. It does not necessarily represent the perspective of investors, who would consider only available revenue streams, which may also include subsidies and other support measures, such as special tax provisions, that are not included in the VALCOE.

Figure 19: Moving beyond the LCOE, to the value-adjusted LCOE



The impact of the value adjustment varies by technology depending on operating patterns and system-specific conditions. Dispatchable technologies that operate only during peak times have high costs per MWh, but also relatively high value per MWh. For baseload technologies, value tends to be close to the system average and therefore they have a small value adjustment. For variable renewables, the value adjustment depends mainly on the resource and production profile, the alignment with the shape of electricity demand and the share of variable renewables already in the system. Different operational patterns can be accounted for in the VALCOE, improving comparisons across dispatchable technologies.

The VALCOE is composed of LCOE and energy, capacity as well as flexibility value. Its calculation goes as follows:

$$VALCOE_x = LCOE_x + \overbrace{\overbrace{[\bar{E} - E_x]}^{Energy\ value} + \overbrace{[\bar{C} - C_x]}^{Capacity\ value} + \overbrace{[\bar{F} - F_x]}^{Flexibility\ value}}^{Value\ adjustments}$$

The adjustment for energy value $[E_x]$ of a technology x (or generation unit) is the difference between the individual unit to the system average unit $[\bar{E}]$. $[E_x]$ is calculated as follows:

$$Energy\ value_x \left(\frac{\$}{MWh}\right) = \frac{\sum_h^{8760} \left[WholesalePrice_h \left(\frac{\$}{MWh}\right)\ x\ \ Output_{x,h}\ (MW)\right]}{\sum_h^{8760} Output_{x,h}\ (MW)}$$

Wholesale electricity prices and output volumes for each technology x in each hour h of the year are simulated. Wholesale prices are based on the marginal cost of generation only and do not include any scarcity pricing or other cost adders, such as operating reserves demand curves present in US markets. Hourly models are applied for the United States, European Union, China and India. For other regions, wholesale prices and output volumes are simulated for the four segments of the year presented in section 4.1.2.

The adjustment for capacity value $[C_x]$ of a generation unit is calculated as follows:

$$Capacity\ value_x \left(\frac{\$}{MWh}\right) = \frac{Capacity\ credit_x \quad x \quad Basis\ capacity\ value\ (\$/kW)}{(capacity\ factor_x \quad x \quad hours\ in\ year/1000)}$$

The Capacity credit reflects the contribution to system adequacy and it is differentiated for dispatchable versus renewable technologies:

- Dispatchable power plants = (1-unplanned outage rate by technology)
- Renewables = analysis of technology-specific values by region with hourly modelling

The Basis capacity value is determined based on simulation of capacity market, set by the highest "bid" for capacity payment. Positive bids reflect the payment needed to fill the gap between total generation costs (including capital recovery) and available revenue.

The Capacity factor is differentiated by technology:

- Dispatchable power plants = modelled as simulated operations in previous year
- Wind and solar PV = aligned with latest performance data from IRENA and other sources, improving over time due to technology improvements
- Hydropower and other renewables = aligned with latest performance data by region and long-term regional averages

The flexibility value $[F_x]$ of a generation unit is calculated as follows:

$$Flexibility\ value_x \left(\frac{\$}{MWh}\right) = \frac{Flexibility\ value\ multiplier_x \quad x \quad Base\ flexibility\ value \left(\frac{\$}{kW}\right)}{(capacity\ factor_x \quad x \quad hours\ in\ year/1000)}$$

- The Flexibility value multiplier by technology is based on available market data and held constant over time. Targeted changes in the operations of power plants to increase flexibility value are not represented.
- The Base flexibility value is a function of the annual share of variable renewables in generation, informed by available market data in the EU and US. The flexibility value is assumed to increase with rising VRE shares, up to a maximum equal to the full fixed capital recovery costs of a peaking plant.

Advantages and limitations of the VALCOE

VALCOE has several advantages over the LCOE alone:

- It provides a more sophisticated metric of competitiveness incorporating technology-specific information and system-specific characteristics
- It reflects information/estimations of value provided to the system by each technology (energy, capacity/adequacy and flexibility)
- It provides a robust metric of competitiveness across technologies with different operational characteristics (e.g. baseload to peaking, or dispatchable to variable)
- It provides a robust metric of competitiveness with rising shares of wind and solar PV

However, network integration costs are not included, nor are environmental externalities unless explicitly priced in the markets. Fuel diversity concerns, a critical element of electricity security, are also not reflected in the VALCOE.

The VALCOE approach has some parallels elsewhere, in other approaches used for long-term energy analysis, as well some real-world applications. Optimisation models implicitly represent the cost and value of technologies, but may be limited by the scope of costs included, such as those related to ancillary services. Other long-term energy modelling frameworks, such as the NEMS model used by the US Department of Energy, have incorporated cost and value in capacity expansion decisions. In policy applications, in the auction schemes in Mexico, average energy values for prospective projects have been simulated and used to adjust the bid prices, seeking to identify the most cost-effective projects.

Financing costs for utility-scale solar PV

The declining costs of solar PV have been impressive, with innovation driving down construction costs by 80% from 2010 to 2019 (IRENA, 2020). Cost reductions have been complemented by improved performance resulting from higher efficiency panels and greater use of tracking equipment. Financing costs, however, have received little attention despite their importance. The weighted average cost of capital (WACC) can account for until half of the levelised cost of electricity (LCOE) of utility-scale solar PV projects.

WEO-2020 focused on financing cost through an extensive work based on data from financial markets and academic literature, and on the analysis of auction results and power purchase agreements (PPAs), complemented by a large number of confidential interviews with experts and practitioners around the world. The analysis found that in 2019, WACCs for new utility-scale solar PV projects with revenue support stood at 2.4-4.5% in Europe and the United States (in real terms, pre-tax), 3.4-3.6% in China and 5.0-6.6% in India. The analysis of business models draws on the key revenue risk components – price, volume and off-taker risk – and their implications for the cost of capital. It focuses on models where prices paid for solar generation are defined largely by policy mechanisms, which support the vast majority of deployment worldwide. The findings of this analysis on the prevailing average costs of capital in major solar PV markets underpin the projections in the IEA World Energy Model. Full merchant projects (without any form of price guarantee external to markets) were considered as a point of comparison and an indicative WACC provided, though to date this model remains somewhat theoretical for solar PV. In the longer term, this type of investment may become more common.

Electricity transmission and distribution networks

The model calculates investment in transmission and distribution networks. Transmission networks transport large volumes of electricity over long distances at high voltage. Most large generators and some large-scale industrial users of electricity are connected directly to transmission networks. Distribution networks transform high-voltage electricity from the transmission network into lower voltages, for use by light-industrial, commercial, and domestic end-users.

Investment in grid infrastructure are driven by three factors: investment in new grid infrastructure to accommodate growing demand, investment to replace or refurbish assets that reach the end of their operational lifetime and investments required to integrate renewables in the power sector.

Investment due to electricity demand growth

New investment due to growth in electricity demand is assumed to scale with increase in electricity demand. This calculation is performed for distribution and transmission networks separately and for each region, as the increase in line length per region depends on a number of region-specific factors (e.g. population density).

The investment per type (transmission and distribution) is calculated as follows:

$$Investment^{new} = (\beta \quad \cdot Increase\ in\ power\ generation) \cdot Line\ costs$$

The term β , which reflects the additional amount of network length needed for each additional unit of generation, is estimated for each region using data on network length and generation for the period 1970-2018.[6] The unit costs of addition transmission or distribution lines are derived from observed capital expenditure data. For future years we assume that the real unit cost of networks increases as labour costs increase, taking into account the differences in labour costs between countries.

Investment due to ageing infrastructure

Assuming an average lifetime of 40 years, the amount of grid infrastructure in need for refurbishment is determined and the corresponding investment is calculated

$$Investment^{age} = Line\ length\ reaching\ 40\ years * (Line\ costs * reduction\ factor)$$

Because building new assets entails additional costs to those entailed in refurbishing them, a region-specific cost reduction factor is introduced.

Additional investment due to renewables

A considerable amount of the capacity additions projected over the WEO period is from renewables. The geographical location of these technologies is often strongly influenced by the location of the underlying resource (e.g. areas where the wind is strong or insolation is high), which may not be close to existing centres of demand. In addition, some of these technologies, mainly solar PV, are connected at the end-user side of the grid infrastructure. This modular deployment of generation capacity can lead to increase distribution capacity needs.

Because the introduction of large quantities of remote or variable renewables was not a marked feature of the historic development of electricity networks (with the exception of regions where remote hydroelectricity represents a large proportion of the generation mix), the addition of more renewables is likely to increase the average length of network additions and the cost of transmission and distribution per unit of energy.

Additional transmission network costs are derived based on specific renewable grid integration costs, derived from a literature review. For example for wind, the typically range between \$100 and \$250 per kW of installed wind capacity. Regional differences due to geography and labour costs are taken into account.

The estimation of costs of distribution grid extensions for renewables contains a lot more uncertainties than the transmission grid costs, as less data or studies are available on the technically complex distribution network is available and own use of distributed generation can in turn lead to a reduced need for distribution grid infrastructure. Therefore, we assume, that additional network investment is required only if the electricity generated from distributed generation, such as solar PV in buildings and bioenergy in industry, exceeds local demand and is fed back to the system.

Investment for digitalisation of grid operations

The estimation of the share of digital electricity grids investment by scenario builds on historical data collected from TSOs, electricity network service providers and smart grid actors.

[6] The data on historic network size and capital expenditure stems from Global Transmission & Distribution Report (2020) and NRG Expert (2019).

Hourly model

To quantify the scale of the challenge arising from the integration of high shares of VRE and to assess which measures could be used to minimise curtailment, a new hourly model has been developed for *WEO-2016*, to provide further insights into the operations of power systems. The model builds upon the annual projections generated in the WEM and makes it possible to explore emerging issues in power systems, such as those that arise as the share of VRE continues to rise. The model then feeds the main WEM model with information about additional constraints on the operations of different power plants. The model is a classical hourly dispatch model, representing all hours in the year, setting the objective of meeting electricity demand in each hour of the day for each day of the year at the lowest possible cost, while respecting operational constraints.[7] All 106 power plant types recorded in the WEM and their installed capacities are represented in the hourly model, including existing and new fossil-fuelled power plants, nuclear plants and 16 different renewable energy technologies. The fleet of power plants that is available in each year is determined in WEM and differs by scenario, depending on the prevalent policy framework. These plants are then made available to the hourly model and are dispatched (or chosen to operate) on the basis of the short-run marginal operating costs of each plant (which are mainly determined by fuel costs as projected in WEM) to the extent required to meet demand. The dispatch operates under constraints: there are minimum generation levels to ensure the flexibility and stability of the power system and to meet other needs (such as combined heat and power); the variability of renewable resources (such as wind and solar) determines the availability of variable renewables and, hence, the maximum output at any point in time; and ramping constraints apply, derived from the level of output in the preceding hour and the characteristics of different types of power plants. The hourly dispatch model does not represent the transmission and distribution system, nor grid bottlenecks, cross-border flows or the flow of power through the grid. It therefore simulates systems that are able to achieve full integration across balancing areas in each WEM region (e.g. United States, European Union, China and India).

Key inputs to the model include detailed aggregate hourly production profiles for wind power and solar PV for each region, which were generated for the WEO by combining simulated production profiles for hundreds of individual wind parks and solar PV installations, distributed across the relevant region [8] The individual sites were chosen to represent a broad distribution within a region, allowing the model to represent the smoothing effect achieved by expanding balancing areas. On the demand side, the model uses a detailed analysis, with hourly demand profiles for each specific end-use (such as for lighting or water heating in the residential sector), coupled with the annual evolution of electricity demand by specific end-use over the *Outlook* period from the main WEM model (see Section 3.4).

The hourly model accounts for grid, flexible generation and system-friendly development of VRE, in three steps: first, it assesses the amount of curtailment of variable renewables that would occur without demand-side response and storage. Second, it deploys demand-side response measures, based on the available potential in each hour for each electricity end-use. And third, it uses existing and new storage facilities to determine the economic operations of storage based on the price differential across hours and charge/discharge periods. It thereby enables the integration needs arising from growing shares of renewables to be assessed.

Among the other important model outputs is the resulting hourly market price, which can drop to zero in the hours when generation from zero marginal cost generators (such as variable renewables) is sufficient to meet demand. By multiplying the market price by generation output in each hour, the model calculates the revenues received for the output in each hour by each type of plant, creating a basis for calculating the value of VRE.

[7] The model works on an hourly granularity, and therefore all intra-hour values of different devices (e.g. of storage technologies) are not captured.

[8] Wind and solar PV data are from Renewables.ninja (*https://beta.renewables.ninja/*) and Ueckerdt, F., *et. al*. (2016).

Naturally, the model also includes hourly operation information for each plant type, including fuel costs and associated greenhouse-gas and pollutant emissions.

Mini- and off-grid power systems

Since the *Africa Energy Outlook* in 2014, the representation of mini- and off-grid systems, related to those gaining access to electricity, has been improved and better integrated into the WEM. In line with the approach for on-grid power systems, to meet additional electricity demand, the model chooses between available technologies for mini- and off-grid systems based on their regional long-run marginal costs, and using detailed geospatial modelling to take into account several determining factors. For the *Africa Energy Outlook 2019*, the IEA refined its analysis using up-to-date technology costs, demand projections, and the latest version of the Open Source Spatial Electrification Tool (OnSSET)[9] developed by KTH, to cover in detail 44 countries in sub-Saharan Africa. The technologies are restricted by the available resources in each region, including renewable energy resources such as river systems, biomass feedstocks (e.g. forests and agricultural residues), wind and the strength of solar insolation. Back-up power generation for those with access to the grid, typically gasoline or diesel fuelled, was also represented to the model, with its projected use tied to the quality of the on-grid power supply.

Renewables and combined heat and power modules

The projections for renewable electricity generation and combined heat and power (CHP) are derived in separate sub-modules.

Combined heat and power and distributed generation

The CHP option is considered for fossil fuel and bioenergy-based power plants. The CHP sub-module uses the potential for heat production in industry and buildings together with heat demand projections, which are estimated econometrically in the demand modules.

Renewable energy

The projections of renewable electricity generation are derived in the renewables sub-module. The deployment of renewables is modelled based on policy targets, technology competitiveness and resource potential, specified for each technology (bioenergy, hydropower, solar PV, concentrating solar power, geothermal electricity, wind, and marine) in each of the 26 WEM regions.[10] Policy targets are often for specific technologies, for example, over 130 countries have support policies in place to expand the use of solar PV and wind as of 2020. Though others may specify the total contribution of renewable energy, the share of renewables in total electricity generation, or the low emissions share of generation including renewables. In cases where policies specify a broad target that includes renewables, technology competitiveness and resource potentials drive the relative contributions. Technology competitiveness is based on the value-adjusted LCOE (see section above) and applies equally to comparisons amongst renewable energy technologies and a broader set of technologies. Resource potential is considered on a regional basis for each renewable energy technology (see Box 2). Beyond the reach of policy targets, technology competitiveness and resource potentials are the critical considerations for renewables

---

[9] For more details on the Open Source Spatial Electrification Tool, see www.onsset.org; for the latest OnSSET methodology update refer to Korkovelos, A. et al. (2019).

[10] A number of sub-types of these technologies are modelled individually, as follows. Biomass: small CHP, medium CHP, electricity only power plants, biogas-fired, waste-to-energy fired and co-fired plants. Hydro: large (≥10MW) and small (<10MW). Wind: onshore and offshore. Solar PV: large-scale and buildings. Geothermal: electricity only and CHP. Marine: tidal and wave technologies.

deployment. Market constraints, including administrative ones, and technical barriers such as grid constraints where applicable are considered, and are most important in the near term as technologies mature.

Electricity generation from newly built renewables is calculated based on an assessment of historical operations and evolving technology designs. For example, wind turbine designs have improved over the past decade, achieving higher performance under a variety of wind conditions. Assumed capacity factors for new renewable energy projects are technology- and region-specific. Total electricity generation from a renewable technology is the sum of all projects in operation within a given year.

Overnight investment needs for renewables are calculated based on the deployment of renewables and evolving technology costs. Our modelling, in all scenarios, incorporates a process of learning-by-doing for projected capital costs for renewables (and other technologies not yet mature). Learning rates are assumed by decade for specific technologies. The overall evolution of the technology costs are commonly expressed through the LCOE. While technology learning is integral to the approach, the WEO does not try to anticipate technology breakthroughs.

Box 2: Long-term potential of renewables

The starting point for deriving future deployment of renewables is the assessment of long-term realisable potentials for each type of renewable and for each region. The assessment is based on a review of the existing literature and on the refinement of available data. It includes the following steps:

1. The *theoretical* potentials for each region are derived. General physical parameters are taken into account to determine the theoretical upper limit of what can be produced from a particular energy, based on current scientific knowledge.
2. The *technical* potential can be derived from an observation of such boundary conditions as the efficiency of conversion technologies and the available land area to install wind turbines. For most resources, technical potential is a changing factor. With increased research and development, conversion technologies might be improved and the technical potential increased.

Long-term *realisable* potential is the fraction of the overall technical potential that can be actually realised in the long term. To estimate it, overall constraints like technical feasibility, social acceptance, planning requirements and industrial growth are taken into consideration.

Wind offshore technical potential

In collaboration with Imperial College London, a detailed geospatial analysis was undertaken for *WEO-2019* to assess the technical potential for offshore wind worldwide. The study was among the first to use the "ERA-5" reanalysis, which provides four decades of historic global weather data. "Renewables.ninja" extrapolates wind speeds to the desired hub height and converts them to output using manufacturers' power curves for turbine models. Results can be found on the IEA website.

Data

The availability of high-resolution satellite data and computing gains has significantly improved the granularity and accuracy of wind resource assessments in recent years. Emerging wind turbine designs are also cause to update potential assessments, as they increase performance in well-established areas and make lower quality resources more suitable for energy production.

Exclusions

Commercially available offshore wind turbines are currently designed for wind speeds of more than 6 m/s. Some companies are also looking into turbine designs for lower wind speeds.

Following the International Union for Conservation of Nature's (IUCN) classification of maritime protection areas, those categorised as Ia, Ib, II and III were excluded from the study (IUCN, 2013). However, at each project level other environmental considerations must also be taken into account and a full environmental impact assessment conducted as mandated by public authorities. Buffer zones were also excluded for existing submarine cables (within 1 kilometre [km]), major shipping lanes (20 km), earthquake fault lines (20 km) and competing uses such as existing offshore oil and gas installations and fisheries.

Turbine designs

In order to assess the global technical potential, best-in-class turbines were chosen with specific power of 250, 300 and 350 watt per square metre (W/m^2) that corresponds to low-medium, medium and high wind speeds. The power curves of these turbines were used in conjunction with the global capacity factors of each 5 km by 5 km cell selected for the analysis to derive the technical potential of offshore wind in terms of capacity and generation. New power curves were synthesised for next-generation turbines with rated capacity of up to 20 MW, for which data are not yet available (Saint-Drenan et al., 2019).

Further to this, the analysis takes into account further considerations such as offshore wind farm designs, distance from shore and water depth, offshore wind cost developments and the technical potential.

Hydrogen and ammonia in electricity generation

Low-carbon hydrogen and ammonia are fuels that can provide a low emissions alternative to natural gas- and coal-fired electricity generation - either through co-firing or full conversion of facilities. In the WEM, blending levels of hydrogen in gas-fired plants and ammonia in coal-fired plants are specified in line with policy and emissions targets. As part of the scenarios, the shares of hydrogen and/or ammonia blending increase over time, representing both advances in the capability to retrofit existing facilities to co-fire higher shares of hydrogen and/or ammonia, and the uptake of new designs that are designed to higher shares of hydrogen or ammonia, or plants that are purposely designed to run entirely on hydrogen or ammonia.

Increased levels of hydrogen and ammonia blending in the WEM incur additional capital expenditure due to the need for more extensive retrofitting of existing natural gas- and coal-fired power plants.

Electricity sector demand for hydrogen and ammonia is used by the hydrogen transformation module to inform the overall demand for hydrogen production.

Utility-scale battery storage

Utility-scale battery storage in the WEM provides an important source of power system flexibility, particularly important where flexibility needs increase due to evolving electricity demand patterns and rising shares of variable renewables. Lithium-ion batteries dispatch in the hourly model, whereby batteries charging and discharging patterns are optimised based on price arbitrage opportunities (i.e. charging when prices are low and discharging when prices are high). Utility-scale battery storage range from one to eight hours in duration (i.e. number of hours at maximum output). Batteries operate only when the difference between the price received for discharging and price paid for charging within a 24-hour period is greater than a threshold, which is set based on factors such as upfront capital costs, expected lifetime cycles and round-trip efficiency. Similarly to other electricity sector technologies, batteries investment decisions are based on VALCOE, with batteries assumed to have different levels of capacity credit depending on their duration – contributing to system adequacy and flexibility. Utility-scale battery storage can either be stand-alone projects or paired with power plants, such as wind and solar PV.

In the World Energy Outlook 2021, utility-scale battery storage capital costs decline from 310 USD/kWh in 2020 on average globally to 155 USD/kWh in 2030 and 110 USD/kWh in the NZE (for systems rated to provide maximum power output for a four-hour period). Historical capital costs for utility-scale battery storage are updated regularly based on reported industry costs (Bloomberg New Energy Finance, 2020; Cole *et al.* 2021). The degree of technology cost reductions is then calculated based on learning rates from existing literature, applied for the battery pack and for auxiliary components such as invertors and overhead costs.[11] For battery packs, projected costs are driven by the demand for batteries across all sectors, with the largest volume related to the global deployment of electric vehicles. For other components of utility-scale battery storage, projected costs are related to the global deployment within the electricity sector.

[11] Based on Schmidt *et al.* (2017) and Tsiropoulos *et al.* (2018)

5 Other energy transformation

Oil refining and trade

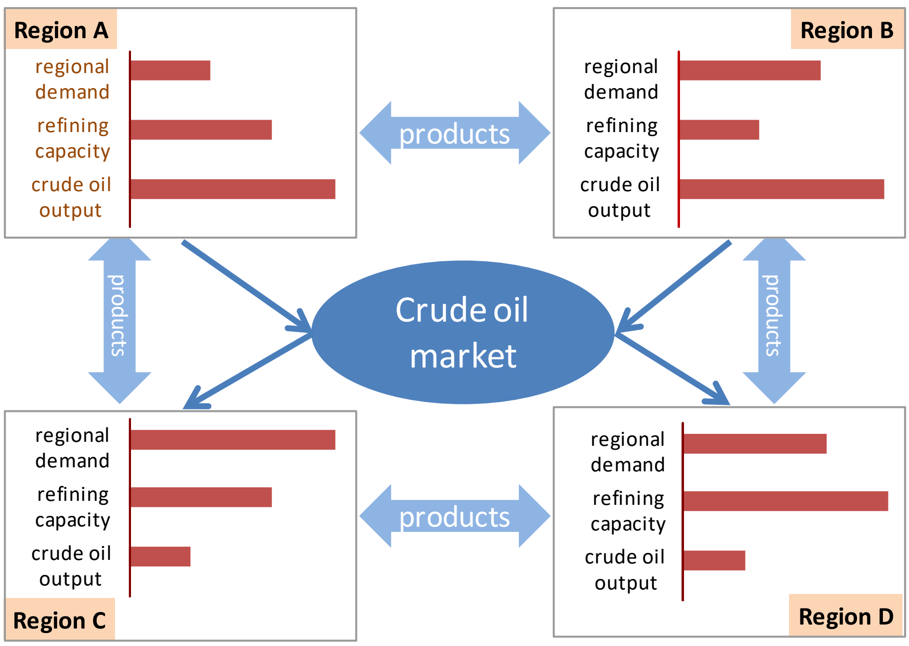
The refinery and trade module links oil supply and demand. It is a simulation model, with capacity development and utilisation modelled for 134 individual countries, with the remaining countries grouped into 11 regions. This module has several auxiliaries that stretch into supply and demand domains to better link both:

- Natural gas liquids module to determine yields of various products as well as condensate.
- Extra-heavy oil and bitumen module to model synthetic crude oil output and diluent requirements for bitumen.
- Split of oil demand into different production categories for all sectors except road transport and aviation. The latter are provided by WEM's transport demand model.

Crude distillation (CDU) capacity is based on 2019 data from the IEA. Capacity expansion projects that are currently announced are assessed individually to identify only the projects that are very likely to go ahead. Some of these are delayed from their announced start-up dates to allow for a more realistic timeline. The model also takes into account refinery closures that have been announced. Beyond 2025, new capacity expansion is projected based on crude availability and product demand prospects for each of the regions specified below.

Projections for refining sector activity are based primarily on CDU capacity and utilisation rates. Secondary unit capacities (such as fluid catalytic cracking, hydrocracking) and run rates, are defined by the required output mix to match product demand. Among oil-importing regions, priority call on international supply of crude oil is given to those where demand is growing: robust domestic demand is effectively a proxy for refinery margins that are not explicitly calculated or used by the model.

Figure 20: **Schematic of refining and international trade module**



Oil output and demand projections are provided by WEM's fossil-fuel supply and final energy consumption modules. Refineries do not provide for 100% of oil product demand. For the purposes of this analysis, we show the net call on refineries after the removal of biofuels, liquefied petroleum gas (LPG), ethane and light naphtha from natural gas liquids (NGL), synthetic liquids from coal-to-liquids (CTL) and gas-to-liquids (GTL) and additives.

The supply-side nomenclature for the refining model is slightly different from the oil supply model. The term "crude oil" used in the model describes all crude oils that have conventional-type quality for processing purposes. This includes conventional crude oil from the supply model, some extra heavy oils that are not diluted or upgraded, tight oil and synthetic crude from bitumen upgrading processes. Diluted bitumen and condensate are represented as separate streams for intake and trade modelling purposes.

Yields, output and trade are defined for the following product categories: LPG, naphtha, gasoline, kerosene, diesel, heavy fuel oil and other products (which include petroleum coke, refinery gas, asphalt, solvents, wax, etc). Vacuum gas oil is added to the middle distillates pool for trade flow purposes. Crude oil trade position refined products balances follow WEO's demand model granularity of 26 individual countries or regions (Figure 20).

Coal-to-liquids, Gas-to-liquids, Coal-to-gas

Coal and natural gas are hydrocarbons that can be transformed to other hydrocarbons through thermal and/or catalytic processes. The most common example is the Fischer-Tropsch reaction, which transforms syngas – a mixture of carbon monoxide and hydrogen mainly – into carbon chains of 5 to 20 carbons. The syngas is produced by a high temperature and relatively high pressure process called gasification. The syngas can also be used to produce methane via Sabatier reaction – in that case the transformation is called coal-to-gas.

These technologies are relatively costly, especially in CAPEX, and therefore require very cheap coal or gas to compete with international markets. They are also developed to increase energy sufficiency and sovereignety in large consumer countries. Best example is China. For these two reasons, there is a currently limited number of projects in the pipeline in a limited number of countries. Projections are consistent with the status of the projects – under construction or planned – and are updated every year on a project by project basis.

In *WEO-2020*, accounting of energy-related CO_2 emissions, also known as "process own use", have been aligned with the other energy transformation processes. CCUS assumptions have also been refined to be consistent with other large scale energy models, such as Energy Technology Perspectives model (IEA, 2020b).

Hydrogen production and supply

Hydrogen in today's energy system is predominantly used as a feedstock rather than a fuel, especially in all the situations in which it is used as a purified hydrogen gas. These existing applications are mostly in the refining and chemicals sectors and are modelled as part of the consumption of energy inputs in these WEM modules. Most hydrogen for these existing applications is produced by steam methane reforming of natural gas or coal gasification without CCUS. In WEO scenarios, an increasing share of this hydrogen is produced over time using technologies that have very low CO_2 intensities, including electrolysis and conversion of fossil fuels equipped with CCUS.

In other sectors – including transport, power generation, buildings and industrial heat – hydrogen demand rises in WEO scenarios from very low levels in order to replace fuels that contribute higher CO_2 emissions. In WEM, all of this new hydrogen demand is linked to "low-carbon hydrogen" production and supply. This supply is set to become a key part of the future energy transformation sector, alongside power generation and heat and cooling supply.

Low-carbon hydrogen is hydrogen produced in a way that does not contribute to an increase in atmospheric CO_2 concentrations. Emissions associated with fossil fuel-based hydrogen production are permanently prevented from reaching the atmosphere and the natural gas supply chain must result in very low levels of methane emissions, or the electricity input to hydrogen produced from water must be from renewable or nuclear sources. There are several complementary pathways to produce low-carbon hydrogen, some of which are mature technologies and some of which are at earlier stages of development. The two dominant pathways in WEM are already demonstrated at commercial scales:

- Fossil fuels with CCUS. The typical technology for producing low-carbon hydrogen from fossil fuels with CCUS is steam methane reforming (SMR) of natural gas equipped with CO_2 capture unit that captures the overwhelming majority of the CO_2 generated by the SMR process. The hydrogen yield can be improved with water gas shift (WGS) reaction to produce carbon dioxide and additional hydrogen from carbon monoxide and water. Adaptations to the SMR process, including autothermal reforming and partial oxidation, can achieve capture rates above 95%. As with other technologies in the WEM, cost and performance improvements are assumed to arise from higher deployment levels. The WEM accounts for the safe transport and permanent geological storage of all of the captured CO_2.
- Electrolysis of water using electricity with very low CO_2 intensity. Electrolysers are a well-established technology to split water into hydrogen and oxygen. There are several technologies under development today that can improve existing processes, and these include variations of alkaline electrolysers, polymer electrolyte membrane (PEM) electrolysers and solid oxide electrolyser cells. Electrolyser capital costs in WEM aim to represent a weighted average of likely deployment shares of these technologies, which all improve with increased deployment, and also include all balance-of-plant and engineering, procurement and construction (EPC) costs, which can represent a high share of total installed costs. Hydrogen produced via electrolysis using electricity from the electricity grid that is not decarbonised is not included in WEM. To reflect this requirement, hydrogen production from dedicated solar PV and wind plants, with reflective full load hours have been included in the WEM as a specific pathway.

The market shares of these two main pathways are assessed on a region-by-region basis, drawing on insights from the ETP model. The shares depend on natural gas prices and availability, renewable potentials and government policy stances. For example, hydrogen strategies, such as those of the EU and Japan, are taken into account, including in terms of whether they target hydrogen imports, exports or domestic self-sufficiency.

The production of low-carbon hydrogen-based fuels – including synthetic liquid fuels like synthetic kerosene or methanol, ammonia and synthetic methane – becomes a key additional component of energy transformation in WEO scenarios. The relative ease of transporting hydrogen-based liquid fuels compared with gaseous hydrogen means that demand can be satisfied by imports where this is cost-effective, and in some cases demand for gaseous hydrogen can be met by importing hydrogen-based fuels rather than gaseous hydrogen. In the case of ammonia, it can in some cases be “cracked” at the point of delivery to regenerate gaseous hydrogen. The WEM takes these dynamics and options into account and draws on insights from the ETP model to project trade in both gaseous hydrogen and hydrogen-based fuels to meet global demand for low-carbon energy, raising low-carbon hydrogen production considerably in potential exporting regions such as Australia, Latin America and the Middle East. The carbon inputs for carbon-containing hydrogen-based fuels in the WEM come from sources that are compatible with very low CO_2 intensity throughout the supply chain, including co-products, without offsets. These sources include direct air capture (DAC) and biogenic carbon.

The WEM low-carbon hydrogen supply module interfaces with several other WEM modules. The most notable of these is the power generation module, which is both a source of demand for hydrogen and hydrogen-based fuels, and also an input (alongside natural gas) to satisfying hydrogen production needs at lowest cost. The feedbacks across this interface are performed iteratively. Demand for hydrogen and hydrogen-based fuels in each sector is determined within each sectoral module, with iteration to update hydrogen supply costs based on overall demand where relevant. Average infrastructure costs for pipelines, storage, shipping and refuelling are estimated per unit of hydrogen supplied.

6 Energy supply

Oil

The purpose of this module is to project the level of oil production in each country through a partial bottom-up approach[12] building on:

- the historical series of production by countries;
- standard production profiles and estimates of decline rates at field and country levels derived from the detailed field-by-field analysis first undertaken in *WEO-2008* and updated since;
- an extensive survey of upstream projects sanctioned, planned and announced over the short term in both OPEC and Non-OPEC countries, including conventional and non-conventional reserves, as performed by the IEA Oil Market Report team; this is used to drive production in the first 5 years of the projection period (a summary of the differences in methodology between WEO and the Medium-Term Oil Market Report is included as Box 3);
- a methodology, which aims to replicate as much as possible the decision mode of the industry in developing new reserves by using the criteria of net present value of future cash flows;
- a set of economic assumptions discussed with and validated by the industry including the discount rate used in the economic analysis of potential projects, finding and development costs, and lifting costs;
- an extensive survey of fiscal regimes translating into an estimate of each government's take in the cash flows generated by projects; and
- values of remaining technically recoverable resources (Table 6) calculated based on information from the United States Geological Survey (USGS), BGR and other sources.

The paragraphs below describe how the USGS data are used in the WEM. USGS publishes its World Petroleum Assessment, a thorough review of worldwide conventional oil (and gas) resources. In it, USGS divided the resources into three parts:

- Known oil, which contains both cumulative production and reserves in known reservoirs.
- Undiscovered oil, a basin-by-basin estimate of how much more oil there may be to be found, based on knowledge of petroleum geology.
- Reserves growth, an estimate of how much oil may be produced from known reservoirs on top of the known reserves. As the name indicates, this is based on the observation that estimates of reserves (including cumulative production) in known reservoirs tend to grow with time as knowledge of the reservoir and technology improves. For the 2000 assessment, reserve growth as a function of time after discovery was calibrated from observation in US fields, and this calibration applied to the known worldwide reserves to obtain an estimate of worldwide reserves growth potential.

Since the 2000 assessment, USGS has regularly published updates on undiscovered oil in various basins, and these were considered in the WEM. In 2012, USGS published an updated summary of worldwide undiscovered oil, as well as a revised estimate for reserves growth based on a new field-by-field method focused on the large fields in the world. Previously the known oil estimates used by the USGS when generating its reserve growth estimates had not been released publicly. However, a recent report provides its assumptions, albeit aggregated at a global level (USGS, 2015). The USGS estimate of cumulative production and reserves outside the United States is 2 060 billion barrels, which is in close alignment with the IEA equivalent estimate of 2 050 billion barrels. For conventional oil, the USGS estimates of undiscovered oil and reserves growth published in 2012 provide the key foundation for the values used in WEM. The WEM estimates of remaining technically recoverable resources

[12] "Bottom-up" in this context means "based on field-by-field analysis".

combine USGS undiscovered, USGS reserves growth and IEA estimates for known. A similar analysis, based on the same USGS publications, feeds into the IEA NGLs and natural gas resources database, which allows looking at total conventional liquid hydrocarbons resources and conventional gas resources.

Box 3: WEO differences in methodology compared with the Medium-Term Oil Market Report

The IEA publishes annually projections of oil supply and demand for the next five years in the Medium Term Oil Market Report (MTOMR), and for the next two and half decades in the WEO. Those two sets of projections use different methodologies that evolve every year. This makes comparisons not straightforward for some readers. This box summarizes the key differences.

A very important difference between MTOMR and WEO is the oil price assumption. MTOMR assumes that the oil price follows the futures market curve at the time of publication; this is then used for the demand projection, and supply is assumed to follow, with OPEC filling the gap between field-by-field projections of non-OPEC supply and demand. WEO determines the equilibrium price that brings supply and demand in balance. However, to avoid generating investment/price cycles which would obscure policy effects and long term trends, this equilibrium is performed as a trend and not year-by-year.

WEO relies on the field-by-field analysis of MTOMR to guide production by country in the first five years of the projection period. The country by country methodology is also extended to OPEC countries, so OPEC is not treated as the swing producer, though constraints thought to represent possible OPEC policies are incorporated in the WEM oil supply module.

Results are also often presented slightly differently in the two reports. Conventional and unconventional oil may be grouped differently with WEO including all of Canadian oil sands and Venezuelan Orinoco production in unconventional, while MTOMR generally counts only upgraded bitumen or extra-heavy oil as unconventional.

In analysing and projecting oil demand, WEO and MTOMR have methodological differences. Since WEO is concerned with projections of supply and demand of all energy sources and projects a world energy balance in the future, it incorporates all demand components. Due to the nature of these components, they can be with a plus or a minus sign (i.e. increasing or decreasing the demand figure). Therefore, while WEO incorporates statistical differences and refinery transformation losses into historical demand values and projects those into the future, MTOMR's demand definition does not include these two categories in its historical values and projections.

WEO also splits biofuels from historical oil demand and projects oil demand and biofuels demand separately. OMR does not separate biofuels from the historical oil demand, and the oil demand is projected with a mix of biofuels. As a result, one barrel of oil from MTOMR projections has lower energy content than that of WEO if biofuels are projected to grow. A direct comparison of WEO and OMR results is thus only possible if biofuels are stripped off MTOMR values of oil demand.

The differences in refining mainly concern the interpretation of installed capacity. WEO discounts most of idled capacity of Chinese teapot and smaller refineries that run below 30% utilization rates. It also discards the mothballed capacity in entirety, even if the owner of the refinery has announced that it is a temporary economic shutdown. MTOMR and WEO may also differ in their projection of firm capacity additions within the same timeframe.

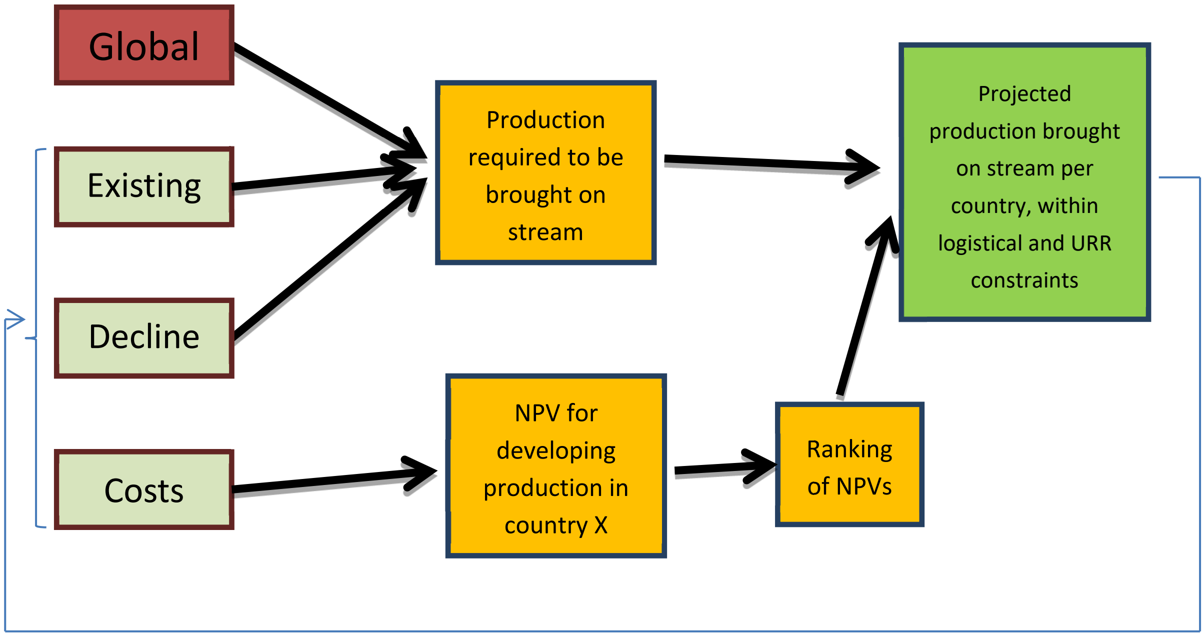
Each country's projected oil production profile is made of six components. Conventional crude oil fields are also distinguished by water depth (onshore, shallow [water depth less than 450 metres], deepwater [between 450-

1 500 metres] and ultra-deepwater [greater than 1 500 metres]). For unconventional oil, extra-heavy oil and bitumen is also distinguished by mining or *in situ* technologies and tight oil by play productivity.

- Production from currently producing fields as of an estimated end-2021: the projected decline rates in each country are derived from the analysis summarised in Box 4;
- Production from discovered fields with sanctioned, planned and announced developments;
- Production from discovered fields awaiting development;
- Production from fields yet to be discovered;
- Production of natural gas liquids; and
- Production of unconventional oil.

Trends in oil production are modelled using a bottom-up methodology, making extensive use of our database of worldwide ultimately technically recoverable resources. The methodology aims to replicate investment decisions in the oil industry by analysing the profitability of developing reserves at the project level (Figure 21).

Figure 21: Structure of the oil supply module



In the WEM oil supply module, production in each country or group of countries is separately derived, according to the type of asset in which investments are made: existing fields, new fields and non-conventional projects. Standard production profiles are applied to derive the production trend for existing fields and for those new fields (by country and type of field) which are brought into production over the projection period.

The profitability of each type of project is based on assumptions about the capital and operating costs of different types of projects, and the discount rate, representing the cost of capital. The net present value of the cash flows of each type of project is derived from a standard production profile. Projects are prioritised by their net present value and the most potentially profitable projects are developed. Constraints on how fast projects can be developed and how fast production can grow in a given country are also applied. These are derived from historical data and industry inputs. When demand cannot be met without relaxing the constraints, this signals that oil prices need to be increased.

US tight oil model

A tight oil module is part of WEM since *WEO-2016* and it explores the sensitivity of production of tight oil in the United States to changes in price and resource availability. The module projects possible future production across 23 shale plays taking into account the estimated ultimate recovery (EUR), initial production, rate of decline and drilling costs of wells drilled and completed across different areas of each play. Existing production is modelled by estimating decline parameters of wells based on latest production information available, and the time when these wells were completed.

Price dynamics affect the number of rigs that are available to drill new wells, with a lag between increases in prices and increases in the number of rigs operating (as observed empirically). Technology increases both the speed at which new wells can be drilled and completed (the number of wells per rig) and the amount of production from each well (the EUR/well). Conversely, the EUR/well of a given area in a given play is assumed to degrade as that area is depleted over time.

Box 4: Methodology to account for production decline in oil and gas fields

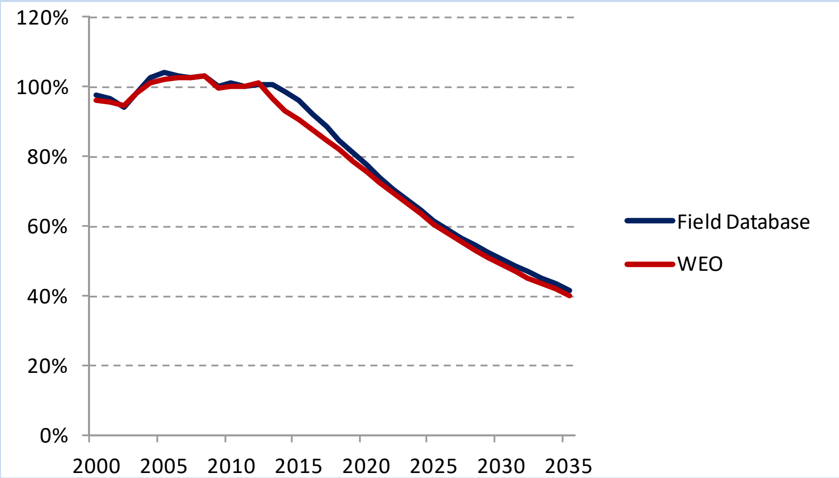
The World Energy Outlook has previously presented analyses of decline rates in oil fields on a number of occasions, based on looking at actual production data time series for a large number of fields. The outcome of this work is a value for observed decline rates by type of field, geographical location and phase of decline, as well as an estimate for the difference between observed decline rates and natural decline rates (the decline rate that would be observed in the absence of further investment in producing fields).

In principle this provides the elements to project the future production of all fields in decline among the set of fields used. The methodology could be as follows:

- For each field in the database, assign a type (super-giant, giant… onshore, offshore, deepwater) and determine the current decline phase.
- Project future production for each field as per corresponding decline rate provided in *WEO-2013*, updating decline rates as the field changes phase.

But this does not allow the projection of world production from all currently producing fields, as one also needs to project production from fields currently ramping up (*i.e.* one needs to know their future peak year and peak production) and from declining fields not in the database. This is done using a proprietary commercial database that contains a representation of possible future production for all fields in the world. Based on this more complete data set, the WEM oil supply module uses a country-by-country parameterisation of natural decline rates (for each resources type) and a production profile for resources developed in each country during the projection period (*i.e.* resources developed in a given year then provide a ramping-up of production, followed by peak and decline). As shown in Figure 22, this parameterization gives a good match with the results of the proprietary database (as the two databases have slightly different base productions, both are normalized to allow a clearer comparison of decline) for the long term decline; in the short term, the IEA field-by-field analysis (coming from the Medium Term Oil Market Report) is more conservative that the commercial database, as it accounts for expected field maintenance and weather disruptions.

Figure 22: **Evolution of production of currently producing conventional oil fields from a field-by-field database and from the WEM**



Source: Rystad Energy AS, IEA analysis and databases.

Rigs are distributed across plays based on current activity, and the expected cost effectiveness of new wells that are drilled. It is assumed that while operators would aim to drill only in their most productive areas, some wells will inevitably be located in regions with lower EUR/well or higher decline rates. The product of numbers rigs, wells/rig, and production/well then gives the new production that comes online in each play in each month starting in January 2020. Results from this module are directly fed into WEM for each of the scenarios implemented.

A similar model was developed for shale gas production in the United States.

Natural gas

Natural gas production and trade projections are derived from a hybrid WEM gas supply module involving bottom-up and top-down approaches. The module has similar inputs, logic and functionality as the oil supply module described above. However, contrary to oil which is assumed to be freely traded globally, gas is assumed to be primarily regionally traded, with inter-regional trade constrained by existing or planned pipelines, LNG plants and long-term contracts. So the module is first run for 20 regions (see Annex 1), for which indigenous production is modelled on the basis of remaining technically recoverable resources (Table 6) and depletion rates, taking account of production costs and prices in the region. Subtracting domestic production from demand, in aggregate for each importing regional block, yields gas import requirements. For each gas net-exporting regional block, aggregate production is determined by the level of domestic demand and the call on that region's exportable production (which is determined by the import needs of the net importing regions and supply costs). Long term contracts (current, or assumed for the future) are served first, then exporting regions compete on the basis of marginal production costs plus transport costs, within the current and assumed future LNG and pipeline capacities. This provides an inter-block gas trade matrix. The effects of pricing policies (current or assumed for the future) of exporting regions can also be taken into account.

Production within each region is allocated to individual countries according to remaining technically recoverable resources, depletion rates and relative supply costs, with a logic similar to that of the oil supply module, but with "demand" being provided by the respective regional production derived in the previous step.

Coal

The coal module is a combination of a resources approach (Table 6) and an assessment of the development of domestic and international markets, based on the international coal price. Production, imports and exports are based on coal demand projections and historical data, on a country basis. Four markets are considered: coking coal, steam coal, lignite and peat. World coal trade, principally constituted of coking coal and steam coal, is separately modelled for the two markets and balanced on an annual basis.

Table 6: Remaining technically recoverable fossil fuel resources, end-2020

Oil (billion barrels)	Proven reserves	Resources	Conventional crude oil	Tight oil	NGLs	EHOB	Kerogen oil
North America	238	2 416	239	217	160	799	1 000
Central and South America	292	860	255	59	49	493	3
Europe	15	114	58	19	28	3	6
Africa	125	446	306	54	84	2	-
Middle East	887	1 146	895	29	178	14	30
Eurasia	146	945	232	85	58	552	18
Asia Pacific	50	279	124	72	64	3	16
World	**1 753**	**6 206**	**2 109**	**536**	**622**	**1 866**	**1 073**

Natural gas (trillion cubic metres)	Proven reserves	Resources	Conventional gas	Tight gas	Shale gas	Coalbed methane
North America	17	149	50	10	81	7
Central and South America	8	84	28	15	41	-
Europe	5	46	18	5	18	5
Africa	19	101	51	10	40	0
Middle East	81	121	101	9	11	-
Eurasia	70	169	131	10	10	17
Asia Pacific	21	139	45	21	53	20
World	**221**	**809**	**425**	**80**	**253**	**49**

Coal (billion tonnes)	Proven reserves	Resources	Coking coal	Steam coal	Lignite
North America	257	8 389	1 031	5 839	1 519
Central and South America	14	60	3	32	25
Europe	137	982	166	413	403
Africa	15	343	45	297	0
Middle East	1	41	19	23	-
Eurasia	191	2 015	343	1 041	632
Asia Pacific	461	8 974	1 509	6 037	1 428
World	**1 076**	**20 803**	**3 115**	**13 682**	**4 007**

Notes: NGLs = natural gas liquids; EHOB = extra-heavy oil and bitumen. The breakdown of coal resources by type is an IEA estimate. Coal world resources exclude Antarctica.

Source: IEA *WEO-2021*.

Bioenergy

Bioenergy is an important renewable energy option in all of its forms: solid (biomass), liquid (biofuels) and gas (biogas and biomethane). Bioenergy provides a significant portion of renewables-based electricity and transport fuels in all scenarios in the WEO and as gas can also contribute to decarbonise the gas network. Many regions or countries have or are considering policies that will increase the demand for bioenergy in the power and transport sectors further in the future.

The Bioenergy supply module, part of WEM since *WEO-2012*, is designed to assess the ability of WEO regions to meet their demand for bioenergy for power generation and biofuels with domestic resources.[13] Where they are not able to do so, the module also simulates the international trade of solid biomass and biofuels. The availability of bioenergy is restricted to renewable sources of biomass feedstock that is not in competition with food.

The Biogas and biomethane supply module, added to the WEM for *WEO-2019*, is designed to assess the sustainable technical potential and costs of biogas and biomethane for all the WEO regions. This analysis includes feedstocks that can be processed with existing technologies, that do not compete with food for agricultural land, and that do not have any other adverse sustainability impacts (e.g. reducing biodiversity). Feedstocks grown specifically to produce biogas, such as energy crops, are also excluded. This module excludes international trades of biogas and biomethane.

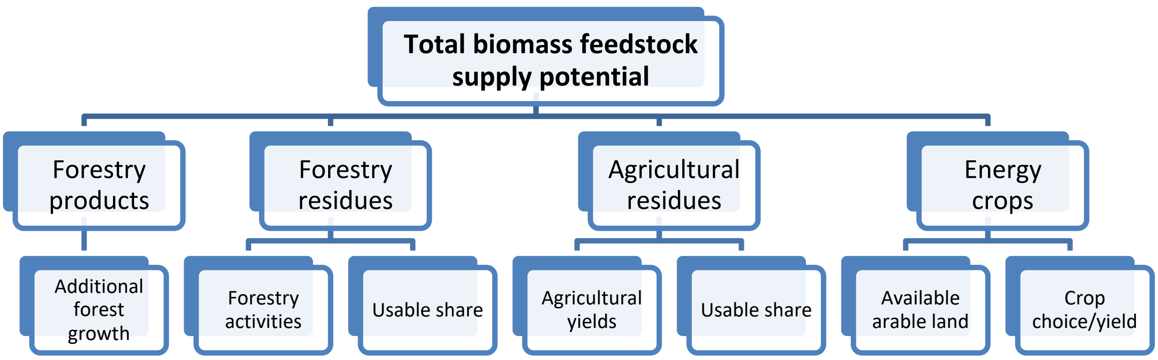
Bioenergy supply module

Biomass supply potentials by region

The feedstock supply potentials are built on a wide range of data related to land, crops and food demand, originating largely from the database of the Food and Agriculture Organization of the United Nations (FAO), as well as academic literature and the Global Agro-Ecological Zones (GAEZ) system, a collaborative project involving FAO and the Institute for Applied Systems Analysis (IIASA).

Total supply potentials by region in the bioenergy supply module are the sum of the potential supply for four categories of feedstocks: forestry products, forestry residues, agricultural residues and energy crops (Figure 23). Starting from current activity levels, ramping up collection and delivery of these often diffuse feedstocks requires significant lead times before maximum potential supply levels can be reached. The potential supply of forestry and agricultural residues is reduced by industrial and residential use to produce heat, as well as demand for traditional uses.

Figure 23: Schematic of biomass supply potentials



[13] The module does not assess demand or supply related to biogas or waste.

Forestry products include only forestry activities, such as harvesting trees and complementary fellings, for the primary purpose of producing power or transport biofuels. The maximum potential availability of forestry products is limited to the expected growth in total forest area per year, after other forestry demands are met, in each region, thereby avoiding direct deforestation.

Forestry residues are those materials, or secondary products, produced from forestry activities where the primary motivation is something other than to produce bioenergy. These include forestry scraps, bark leftover from the timber industry, industrial by-products and waste wood. The maximum potential availability is limited by the level of the related activities and the usable share of the leftover materials.

Agricultural residues are the leftover materials after harvesting crops, such as corn stover, straw and bagasse from sugarcane processing. Data for harvests by region include the following crops: barley, maize (corn), oats, rice, sorghum, wheat, other cereals, rapeseed, soybeans, sunflower seed, and sugarcane. The maximum potential availability is limited by the amount of crops harvested and by the recoverable share of the residues. It is important for a portion of the residues to remain in fields to replenish soil nutrients and maintain yields for future harvests, by helping reduce soil erosion and maintaining water and temperature in the soils. The percentage of these residues that can be made available for energy production in a sustainable manner is region- and crop-specific, and is still being investigated actively.

Energy crops are those grown specifically for energy purposes, including sugar and starch feedstock for ethanol (e.g. corn, sugarcane, and sugar beet), vegetable-oil feedstock for biodiesel (e.g. rapeseed, soybean and oil palm fruit) and lignocellulosic material (e.g. switchgrass, poplar and miscanthus) for advanced biofuels. The maximum potential availability is determined by the available arable land, after taking into account food-related demand for land, crop choice and rising yields over time.

The potential supply from energy crops (million tonnes) is calculated as follows:

$$P_{t,r} = \sum_{l,g,c} \left(x_{t,r,l,g,c} * y_{t,r,l,g,c} * s_{t,r,c} \right)$$

where, for a given year *t* and region *r,*

- $P_{t,r}$ is the potential biomass feedstock supply from energy crops;
- $x_{t,r,l,g,c}$ is the available land by type *l*, grade *g*, and crop *c;*
- $y_{t,r,l,g,c}$ is the crop yield; and
- $s_{t,r,c}$ is the share of available land for each crop.

Available land is divided into three grades of land quality (prime, good and marginal) and three types of land (cultivated, unprotected grassland and unprotected forest land).[14] Lower quality grades of land provide lower crop yields. In this assessment, unprotected forest land is not allowed to be converted to crop lands and so is unavailable for bioenergy purposes. Crop yields are defined by region, reflecting the average growing conditions in a region, and are assumed to continue to improve moderately through 2035. Crop choice is influenced by currently favoured crops for bioenergy, the changing economics of feedstock (through increased yields and relative attractiveness compared to the fossil fuel alternative), and policy development. For example, policy goals for advanced biofuels will increase demand for lignocellulosic energy crops, decreasing the share of land devoted to conventional feedstock.

[14] Classifications and data from Fischer et al. (2011), Scarcity and abundance of land resources: competing uses and the shrinking land resource base. SOLAW Background Thematic Report - TR02.

Supply to meet demand

Demand for biomass feedstock is based on demand projections in the WEO for both the power and transport sectors (demand for other sectors is assumed to be met from domestic resources). To meet demand, domestic supplies are given priority; the remainder is covered through international markets. The model is calibrated to meet existing trade flows reported in a range of industry reports, including the F.O. Licht series "World Ethanol & Biofuel Report", and government reports, such as regional Global Agricultural Information Network (GAIN) reports on biofuels by the US Department of Agriculture.

Domestic supply

Biomass feedstock competes to meet demand on the basis of conversion costs, including feedstock prices and the energy contents of feedstock. Several biomass feedstock types can be used for both power generation and the production of biofuels. These include forestry products, forestry residues and agricultural residues. Where this is the case, the net present values for both uses are compared and ranked, based on technology cost data from WEM and IEA's Mobility Model. According to rank, available biomass feedstock supplies are allocated. Domestic supply of biofuels is limited by refining capacity. In the near term, this is restricted by existing refineries and those already under construction or planned.

Global trade

The model uses a global trade matrix to match unsatisfied demand with available supply on a least-cost basis, including transportation costs. Transportation costs between regions include both average over-land and by-sea costs. Three products are traded: ethanol, biodiesel and solid biomass pellets. The latter are high-density uniform products that can be made from residues and other feedstock, and their uniformity and density make handling and transportation easier and less expensive over long distances compared with other bioenergy resources. The conversion of biomass feedstock to biofuels occurs in the exporting region, therefore conversion costs are calculated based on the technology costs in the exporting region. Importing regions choose suppliers based on least-cost available supplies (including transportation costs). Exporting regions make supplies available to importing regions willing to pay the highest price.

Biogas and biomethane supply module

Biogas and biomethane supply potential has been assessed considering a wide variety of feedstock, grouped in six categories: crop residues, animal manure, municipal solid wastes (MSW), forest product residues, wastewater and industrial wastes.

The feedstock supply potentials are built on a wide range of data originating largely from the Food and Agriculture Organization of the United Nations (FAO) database and OECD-FAO study (OECD/FAO, 2018) for wheat, maize, rice, other coarse grains, sugar beet, sugar cane, soybean, and other oilseeds, cattle, pig, poultry and sheep, log felling residues, wood processing residues and distiller dried grains (DDGs), a by-product of ethanol production from grains and from a World Bank study (World Bank, 2018) for different categories of organic municipal solid waste such as food and green waste, paper and cardboard, and wood. Wastewater includes only municipal wastewater and is based on the output data from the Water module developed by the World Energy Outlook team.

Biogas is produced by anaerobic digestion. Five technologies of centralised biogas production plants are modelled: landfill gas recovery system, digester in municipal wastewater treatment plant and three centralised co-digestion plants (small-, medium and large-scale). In addition, two types of household-scale digester are modelled in the residential sector of the World Energy Model, to account for rural and decentralised biogas production in rural areas of developing economies.

For biomethane, two production pathways are considered: upgrading of biogas produced by anaerobic digestion and thermal gasification and methanation of lignocellulosic biomass.

For each technology technical and economic parameters, e.g. efficiency, lifetime, overnight capital cost or operational costs are collected to assess the production costs.

The combination of the assessment of the supply potential and the economic evaluation of the different biogas and biomethane processes were used to assess biogas and biomethane supply cost curves. For a given year, it is made of the aggregation of biomethane potential and associated levelised cost of production for every region, feedstock and technology. Information provided by supply curves is then used to assess the cost-competitiveness of the two main uses of biogas and biomethane: electricity and heat generation and injection in the gas grid. Supply curves are used to calculate GHG emissions potential savings and related abatement cost to understand the future role of carbon pricing on biogas and biomethane development.

7 Emissions

CO_2 emissions

As energy-related CO_2 emissions account for the lion's share of global greenhouse gas emissions, one of the important outputs of the WEM is region by region CO_2 emissions from fuel combustion and from industrial processes. Carbon dioxide emissions from fuel combustion and from industrial processes do not include fugitive emissions from fuels, flaring or CO_2 from transport and storage. Unless otherwise stated, CO_2 emissions in the *World Energy Outlook* refer to energy-related and industrial process CO_2 emissions. WEM CO_2 emissions accounting also consider carbon dioxide removal from the atmosphere, also known as Direct Air Carbon Capture, Utilisation and Storage (DAC). Captured CO_2 emissions can be stored in underground geological formations, onshore or offshore or used as an input or feedstock in manufacturing. For each WEM region, sector and fuel, CO_2 emissions from fuel combustion are calculated by multiplying energy demand by an implied CO_2 content factor. The implied CO_2 content factors for coal, oil and gas differ between sectors and regions, reflecting the product mix and efficiency. They have been calculated as an average of the past three years from IEA energy-related sectoral approach CO_2 data for all WEM regions and are assumed to remain constant over the projection period.

For the *WEO* Special Report *Energy and Climate Change*, a detailed analysis of process-related CO_2 emissions from various industrial sources by WEM region was conducted. For the estimation a Tier 1 or Tier 2 method has been used, which in general means that emissions have been estimated based on the production of industrial materials and an emissions factor from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. So far the analysis is limited to the most important sources of industrial process emissions:

- Mineral industry: clinker, lime, limestone use, soda ash use
- Metal industry: primary aluminium
- Chemical industry: ammonia, methanol, ethylene, soda ash
- Non-energy products: lubricants and paraffin
- Transformation: coal-to-liquids, coal-to-gas and gas-to-liquids, hydrogen production, biofuels production (which can bring Carbon Dioxide Removal).

Non-CO_2 greenhouse gases

The WEM models all energy-related GHG emissions, both CO_2 and non-CO_2. Non-CO_2 emissions originating from non-energy sectors rely on the scenarios from the IPCC 5th Assessment Report scenario database. This database contains projections of non-CO_2 emissions over the 21st century under a wide range of scenarios. The CO_2 and non-CO_2 emissions modelled within WEM are benchmarked against scenarios from this database to provide commensurate projections for all other GHGs. This includes projections for other methane emissions, nitrous oxide (N_2O), and F-gases. The last category includes hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6) from several sectors, mainly industry. Where needed, the trajectory of CO_2 emissions from land-use change and forestry (LULUCF) (see Emissions section in Selected updates for the World Energy Outlook 2021) are again taken from scenario databases provided by the IPCC.

Air pollution

Emissions of major air pollutants resulting from the WEO energy scenarios have been estimated in co-operation with the International Institute for Applied Systems Analysis (IIASA). Using the IIASA GAINS model, estimates have been made for the following local air pollutants: sulphur dioxide (SO_2), nitrogen oxides (NO_x), black carbon and $PM_{2.5}$.[15] More information can be found in the WEO Special Report on Energy and Air Pollution as well as in a previous detailed report outlining the approach, results and information about health impacts, as well as pollution control costs.

Global temperature impacts

The average global surface temperature rise that would result from greenhouse gas and aerosol emissions in WEO scenarios has been carried out in close co-operation with Climate Resource Pty Ltd using the *Model for the Assessment of Greenhouse Gas Induced Climate Change* ("MAGICC"),[16] and drawing on other tools used by the global scientific community. The MAGICC climate models have been used extensively in assessment reports written by the Intergovernmental Panel on Climate Change. MAGICC7, the version used in this analysis, is used in the IPCC's Sixth Assessment Report (IPCC, 2021) and described in Cross-Chapter Box 7.1 therein. Emissions of all energy-related greenhouse gases from the *WEO-2021* scenarios are supplemented with commensurate changes in non-energy-related emissions taken from the scenario database published as part of the IPCC Special Report on Global Warming of 1.5 °C (IPCC, 2018).

Oil and gas methane emissions model

Global estimate of methane emissions from oil and gas operations

Our approach to estimating methane emissions from global oil and gas operations relies on generating country-specific and production type-specific emission intensities that are applied to production and consumption data on a country-by-country basis. Our starting point is to generate emission intensities for upstream and downstream oil and gas in the United States (Table 7). The 2020 US Greenhouse Gas Inventory is used for this along with a range of other data sources, including our survey of companies and countries. The hydrocarbon-, segment- and production-specific emission intensities are then further segregated into fugitive, vented and incomplete flaring emissions to give a total of 19 separate emission intensities.

[15] Fine particulate matter is particulate matter that is 2.5 micrometres in diameter and less; it is also known as $PM_{2.5}$ or respirable particles because they penetrate the respiratory system further than larger particles.

[16] Information sourced to Climate Resource in *WEO-2021* was contributed by Climate Resource Pty Ltd using MAGICC7. Neither Climate Resource nor any of its officers, employees, contractors or affiliates make any warranty or guarantee about the accuracy, completeness or reliability of the climate data provided and any liability resulting from its use is the sole responsibility of the reader.

Table 7: Categories of emission sources and emissions intensities in the United States

Hydrocarbon	Segment	Production Type	Emissions Type	Intensity (mass CH_4/mass oil or gas)
Oil	Upstream	Onshore conventional	Vented	0.34%
Oil	Upstream	Onshore conventional	Fugitive	0.03%
Oil	Upstream	Offshore	Vented	0.23%
Oil	Upstream	Offshore	Fugitive	0.02%
Oil	Upstream	Unconventional oil	Vented	0.86%
Oil	Upstream	Unconventional oil	Fugitive	0.08%
Oil	Downstream		Vented	0.004%
Oil	Downstream		Fugitive	0.001%
Oil		Onshore conventional	Incomplete-flare	
Oil		Offshore	Incomplete-flare	
Oil		Unconventional gas	Incomplete-flare	
Gas	Upstream	Onshore conventional	Vented	0.41%
Gas	Upstream	Onshore conventional	Fugitive	0.18%
Gas	Upstream	Offshore	Vented	0.24%
Gas	Upstream	Offshore	Fugitive	0.11%
Gas	Upstream	Unconventional gas	Vented	0.70%
Gas	Upstream	Unconventional gas	Fugitive	0.31%
Gas	Downstream		Vented	0.12%
Gas	Downstream		Fugitive	0.23%

The US emissions intensities are then scaled to provide emission intensities in all other countries. This scaling is based upon a range of auxiliary country-specific data. For the upstream emission intensities, the scaling is based on the age of infrastructure and types of operator within each country (namely international oil companies, independent companies or national oil companies). For downstream emission intensities, country-specific scaling factors were based upon the extent of oil and gas pipeline networks and oil refining capacity and utilisation. The strength of regulation and oversight, incorporating government effectiveness, regulatory quality and the rule of law as given by the Worldwide Governance Indicators compiled by the World Bank (2020), affects the scaling of all intensities. Some adjustments were made to the scaling factors in a limited number of countries to take into account other data that were made available (where this was considered to be sufficiently robust).

Table 8 provides the resultant scaling factors in the top oil and gas producers (the countries listed cover 95% of global oil and gas production). These scaling factors are directly used to modify the emissions intensities in Table 7. For example, the vented emission intensity of onshore conventional gas production in Russia is taken as 0.41%×1.6 = 0.66%. These intensities are finally applied to the production (for upstream emissions) or consumption (for downstream emissions) of oil and gas within each country.

Table 8: Scaling factors applied to emission intensities in the United States

Country	Oil and gas production in 2020	Oil		Gas	
	mtoe	Upstream	Downstream	Upstream	Downstream
United States	1 504	1.0	1.0	1.0	1.0
Russia	1 116	1.8	1.8	1.6	1.7
Saudi Arabia	612	0.8	0.7	0.8	0.7
Canada	404	0.8	0.6	0.9	0.6
Iran	337	3.2	3.2	2.8	3.1
China	365	1.4	1.4	1.3	1.4
Iraq	220	3.6	4.0	3.4	4.0
United Arab Emirates	220	1.1	0.8	1.1	0.8
Qatar	229	1.1	0.9	1.1	0.9
Norway	195	0.1	0.0	0.0	0.0
Kuwait	150	1.2	1.2	1.2	1.2
Brazil	173	1.3	1.5	1.3	1.5
Algeria	138	3.4	2.9	2.5	2.9
Nigeria	129	2.6	2.6	2.2	2.6
Mexico	120	1.7	1.4	1.3	1.4
Kazakhstan	118	1.4	1.3	1.4	1.3
Australia	143	1.1	0.6	0.7	0.6
Indonesia	89	1.6	1.4	1.3	1.4
Malaysia	85	1.5	0.9	0.9	0.9
United Kingdom	85	0.6	0.2	0.5	0.2
Egypt	79	2.4	2.1	1.9	2.1
Oman	79	1.6	1.1	1.2	1.1
Venezuela	43	7.2	6.7	5.3	6.7
Turkmenistan	81	5.5	6.0	4.8	6.0
Angola	73	2.2	2.7	2.1	2.7

Marginal abatement cost curves

To construct the marginal abatement cost curves presented in *WEO-2018* and in the Methane Tracker Database, the 19 emissions sources listed in Table 7 were further separated into 86 equipment-specific emissions sources (Table 9). The allocation of emissions from each of the 19 emissions sources to these 86 equipment-specific sources was generally based on proportions from the United States. However a number of modifications were made for countries based on other data sources and discussions with relevant stakeholders. Some of the largest changes made were for the proportion of emissions from: pneumatic controllers (which are less prevalent in many countries outside North America), LNG liquefaction (which were assumed to be larger in LNG exporting countries), and associated gas venting.

Table 9: Equipment-specific emissions sources used in the marginal abatement cost curves

Equipment source	Hydrocarbon	Segment
Large Tanks w/Flares	Oil	Upstream
Large Tanks w/VRU	Oil	Upstream
Large Tanks w/o Control	Oil	Upstream
Small Tanks w/Flares	Oil	Upstream
Small Tanks w/o Flares	Oil	Upstream
Malfunctioning Separator Dump Valves	Oil	Upstream
Pneumatic Devices, High Bleed	Oil	Upstream
Pneumatic Devices, Low Bleed	Oil	Upstream
Pneumatic Devices, Int Bleed	Oil	Upstream
Chemical Injection Pumps	Oil	Upstream
Vessel Blowdowns	Oil	Upstream
Compressor Blowdowns	Oil	Upstream
Compressor Starts	Oil	Upstream
Associated Gas Venting	Oil	Upstream
Well Completion Venting (less HF Completions)	Oil	Upstream
Well Workovers	Oil	Upstream
HF Well Completions, Uncontrolled	Oil	Upstream
HF Well Completions, Controlled	Oil	Upstream
Pipeline Pigging	Oil	Upstream
Tanks	Oil	Downstream
Truck Loading	Oil	Downstream
Marine Loading	Oil	Downstream
Rail Loading	Oil	Downstream
Pump Station Maintenance	Oil	Downstream
Pipeling Pigging	Oil	Downstream
Uncontrolled Blowdowns	Oil	Downstream
Asphalt Blowing	Oil	Downstream
Process Vents	Oil	Downstream
CEMS	Oil	Downstream
Production Compressor Vented	Gas	Upstream
Gas Well Completions without Hydraulic Fracturing	Gas	Upstream
Gas Well Workovers without Hydraulic Fracturing	Gas	Upstream
Hydraulic Fracturing Completions and Workovers that vent	Gas	Upstream
Hydraulic Fracturing Completions and Workovers with RECs	Gas	Upstream
Well Drilling	Gas	Upstream
Pneumatic Device Vents (Low Bleed)	Gas	Upstream
Pneumatic Device Vents (High Bleed)	Gas	Upstream
Pneumatic Device Vents (Intermittent Bleed)	Gas	Upstream
Chemical Injection Pumps	Gas	Upstream
Kimray Pumps	Gas	Upstream
Dehydrator Vents	Gas	Upstream
Large Tanks w/VRU	Gas	Upstream
Large Tanks w/o Control	Gas	Upstream
Small Tanks w/o Flares	Gas	Upstream
Malfunctioning Separator Dump Valves	Gas	Upstream
Gas Engines	Gas	Upstream
Well Clean Ups (LP Gas Wells) - Vent Using Plungers	Gas	Upstream
Well Clean Ups (LP Gas Wells) - Vent Without Using Plungers	Gas	Upstream
Vessel BD	Gas	Upstream
Pipeline BD	Gas	Upstream
Compressor BD	Gas	Upstream
Compressor Starts	Gas	Upstream
G&B Station Episodic Events	Gas	Upstream
Pressure Relief Valves	Gas	Upstream
Mishaps	Gas	Upstream

Equipment source	Hydrocarbon	Segment
Recip. Compressors	Gas	Upstream
Centrifugal Compressors (wet seals)	Gas	Upstream
Centrifugal Compressors (dry seals)	Gas	Upstream
Dehydrators	Gas	Upstream
AGR Vents	Gas	Upstream
Pneumatic Devices	Gas	Upstream
Blowdowns/Venting	Gas	Upstream
Reciprocating Compressor	Gas	Downstream
Centrifugal Compressor (wet seals)	Gas	Downstream
Centrifugal Compressor (dry seals)	Gas	Downstream
Reciprocating Compressor	Gas	Downstream
Dehydrator vents (Transmission)	Gas	Downstream
Dehydrator vents (Storage)	Gas	Downstream
Pneumatic Devices (High Bleed)	Gas	Downstream
Pneumatic Devices (Intermittent Bleed)	Gas	Downstream
Pneumatic Devices (Low Bleed)	Gas	Downstream
Pneumatic Devices (High Bleed)	Gas	Downstream
Pneumatic Devices (Intermittent Bleed)	Gas	Downstream
Pneumatic Devices (Low Bleed)	Gas	Downstream
Pipeline venting	Gas	Downstream
Station Venting Transmission	Gas	Downstream
Station Venting Storage	Gas	Downstream
LNG Reciprocating Compressors Vented	Gas	Downstream
LNG Centrifugal Compressors Vented	Gas	Downstream
LNG Station venting	Gas	Downstream
LNG Reciprocating Compressors Vented	Gas	Downstream
LNG Centrifugal Compressors Vented	Gas	Downstream
LNG Station venting	Gas	Downstream
Pressure Relief Valve Releases	Gas	Downstream
Pipeline Blowdown	Gas	Downstream
Mishaps (Dig-ins)	Gas	Downstream

The abatement options included in the marginal abatement cost curves to reduce emissions from these sources are listed in Table 10. We are unable to provide the specific costs and applicability factors for these as it is based on proprietary information gathered by ICF (although see ICF (2016a) and ICF (2016b) for data that has made available publically). Costs were again based upon information from the United States. However labour costs, whether the equipment is imported or manufactured domestically (which impacts the capital costs and whether or not import taxes are levied), and capital costs were modified based on country-specific or region-specific information. Similarly the applicability factors are modified based on other data that is available publically (for example that solar-powered electric pumps cannot be deployed as widely in high-latitude countries).

Leak detection and repair (LDAR) programmes are the key mechanism to mitigate fugitive emissions from the production, transmission or distribution segments of the value chain. The costs of inspection differ depending on the segment in question since it takes longer to inspect a compressor on a transmission pipeline than in a production facility. It is assumed that inspections can be carried out annually, twice a year, quarterly or monthly, with each option included as a separate mitigation option in the marginal abatement cost curves. Annual inspections are assumed to mitigate 40% of fugitive emissions, biannual inspections mitigate an additional 20%, quarterly inspections mitigate an additional 10%, and monthly inspections mitigate an additional 5%. Implementing a monthly LDAR programme therefore reduces fugitive emissions by 85%; the remaining 15% cannot be avoided. As the frequency of implementing each programme increases, so does the cost per unit of methane saved. For example, while the incremental cost of a biannual inspection programme is the same as that of an annual inspection, the incremental volume of methane saved is lower (20% rather than 40%). Nevertheless, LDAR programmes remain some of the most cost-effective mitigation options available, i.e. they tend to comprise a large proportion of the positive net present value options in countries.

Table 10: Abatement options for methane emissions from oil and gas operations

Abatement option
Blowdown Capture and Route to Fuel System (per Compressor)
Blowdown Capture and Route to Fuel System (per Plant)
Early replacement of high-bleed devices with low-bleed devices
Early replacement of intermittent-bleed devices with low-bleed devices
Install Flares-Completion
Install Flares-Portable
Install Flares-Portable Completions Workovers WO HF
Install Flares-Portable WO Plunger Lifts
Install Flares-Stranded Gas Venting
Install Flares-Venting
Install New Methane Reducing Catalyst in Engine
Install Non Mechanical Vapor Recovery Unit
Install Plunger Lift Systems in Gas Wells
Install small flare
Install Vapor Recovery Units
LDAR Gathering
LDAR LDC - Large
LDAR LDC - MRR
LDAR Processing
LDAR Reciprocating Compressor Non-seal
LDAR Transmission
LDAR Wells
Mechanical Pumping for Liquids Unloading
Pipeline Pump-Down Before Maintenance
Redesign Blowdown Systems and Alter ESD Practices
Reduced Emission Completion
Replace Kimray Pumps with Electric Pumps
Replace Pneumatic Chemical Injection Pumps with Electric Pumps
Replace Pneumatic Chemical Injection Pumps with Solar Electric Pumps
Replace with Instrument Air Systems
Replace with Electric Motor
Replace with Servo Motors
Replace with Solenoid Controls
Replacement of Reciprocating Compressor Rod Packing Systems
Route to existing flare - Large Dehydrators
Route to existing flare - Large Tanks
Route to flare - Small Dehydrators
Route to existing flare - Small Tanks
Route Vent Vapors to tank
Wet Seal Degassing Recovery System for Centrifugal Compressors
Wet Seal Retrofit to Dry Seal Compressor
Microturbine
Mini-LNG
Mini-GTL
Mini-CNG

Well-head prices used in net present value calculation

Since natural gas is a valuable product, the methane that is recovered can often be sold. This means that deploying certain abatement technologies can result in overall savings if the net value received for the methane sold is greater than the cost of the technology. Well-head prices are used in each country to determine the value of the methane captured. As described in *WEO-2019,* the marginal abatement cost curves examine this issue from a global, societal perspective. The credit obtained for selling the gas is therefore applied regardless of the contractual arrangements necessary and the prices assume that there are no domestic consumption subsidies (as the gas could be sold on the international market at a greater price). The well-head gas prices used could therefore be substantially different from subsidised domestic gas prices.

Representative average natural gas import prices seen from 2017 to 2021 are the starting point for the well-head prices within each country. To estimate well-head prices over time, each country is assigned to be either an importer or an exporter based on the trends seen in the Stated Policies Scenario. For importing countries, any gas that would be saved from avoiding leaks would displace imports. The well-head price is therefore taken as the import price minus the cost of local transport and various taxes that may be levied (assumed to be around 15% of the import price). For exporting countries, the relevant well-head price is taken as the import price in their largest export market net-backed to the emissions source. For the net-back, allowance is made for transport costs (including liquefaction and shipping or pipeline transport), fees and taxes. For example, in Russia the export price is taken as the import price in Europe ($7.4/MBtu average 2017-2021 price). Export taxes of 40% are then subtracted along with a further $0.5/MBtu to cover the cost of transport by pipeline. This gives a well-head gas price in Russia of about $4.0/MBtu. In the United States and Canada, the well-head price is taken as the Henry Hub price minus 15% (to cover the cost of local transportation and fees).

The costs and revenue for each technology or abatement measure is converted into net present value using a discount rate of 10% and divided by the volume of emissions saved to give the cost in dollars per million British thermal units (MBtu).

Other notes on marginal abatement cost curves

To aid visualisation of the marginal abetment cost curves, the costs and savings from multiple technologies are aggregated together. Within each country, the abatement options that could be applied to each of the 19 emission sources listed in Table 7 are aggregated into three cost steps. These steps roughly represent the cheapest 50% of reductions, the next 30% of reductions and the final of 20% reductions.

Methane Tracker update

There are several emerging technologies and approaches to measurement that appear promising to elevate data available on oil and gas methane emissions—among them are satellites and other aerial detection instruments utilised during measurement campaigns.

Confirming and reconciling bottom-up estimates with direct emissions measurements, via aerial instruments or otherwise, is the best option to hone accurate emissions information and overcome shortcomings associated with any single approach. In this regard, using stationary monitors, ground vehicles, or aerial instruments such as satellites, drones, and planes, can reduce the risk that bottom-up estimates significantly underestimate emissions from a site. In order to have the greatest impact on improving estimation techniques, site-level studies should be sufficiently representative geographically and temporally, publicly reported, and independently verified.

The IEA has stayed abreast of instances of these emerging measurement strategies and worked to integrate results from credible sources into the Methane Tracker where data has become available. The 2020 Tracker update reflects major downward revisions to emissions levels in a handful of jurisdictions—notably Norway and the Netherlands. This was the result of a series of measurement campaigns of methane emissions from oil and gas production in the North Sea—these efforts yielded improvements to the process of inventorying emissions and confirmed estimates generated and reported by Norwegian and Dutch industry operators.

The 2021 update to the Methane Tracker incorporated emissions detected by satellites for the first time. Changes in the atmospheric concentration of methane can be used to estimate the rate of emissions from a source that would have caused such a change. This was done based on data processing by Kayrros, an earth observation firm, to convert readings of concentrations to identify large sources of emissions from oil and gas operations. Reported emissions encompass individual methane sources above 5 tonnes per hour as well as clusters of smaller sources in dense areas (e.g. shale plays).

Large emissions from oil and gas operations that were detected by satellites in 2020 are included in the Methane Tracker for onshore areas in: Algeria, Kazakhstan, Iraq, Russian Federation, Turkmenistan. Emissions detected by satellites are reported as a separate item within the Methane Tracker except for the United States. For the United States, the emissions detected from the Permian and Marcellus shale plays are integrated within total estimates for unconventional oil and gas production. In all countries, emissions are assigned either to upstream or downstream operations based on the geographic location of directly-observed emissions events. These readings are also used to inform estimates of emissions that may be occurring in countries that cannot currently be observed directly by satellites.

The increasing amount of data and information from satellites will continue to improve global understanding of methane emissions levels and the opportunities to reduce them. However, satellites do have some limitations:

- Existing satellites do not provide measurements over equatorial regions, northern areas or for offshore operations. This means that there are a large number of major production areas (e.g. in areas that are often covered with snow) where emissions cannot be directly detected by satellites. The emissions detected by satellites that are included in the Methane Tracker come from areas that provide around one quarter of global oil and gas production in 2020.
- Existing satellites should be able to provide methane readings globally on a daily basis but this is not always possible because of cloud cover and other weather conditions. Sentinel 5P readings for 2020 were also affected by a data outage that reduced the number of direct observations that are currently available (these should be available at a later date). The emissions included in the Methane Tracker are the estimate after an upward revision of directly observed leaks in 2020 to account for the lack of perfect coverage.
- Satellites provide data for large emitting sources. They may fail to capture small-scale emissions sources such as faulty components, which could add up to a large overall amount of emissions.
- The process of using changes in the atmospheric concentration of methane to estimate emissions from a particular source can rely on a large level of auxiliary data and be subject to a high degree of uncertainty.

The country-by-country emissions levels in Methane Tracker include estimates for emissions from large-emitting sources, even if they have not been directly observed by satellite. This is, of course, subject to a high degree of uncertainty, but we do so to ensure that our country-by-county estimates provide a comprehensive picture of all methane emissions sources. As additional data becomes available from measurement campaigns – whether recorded from ground or aerial processes or by satellites – we will incorporate these into the Methane Tracker and adjust estimates accordingly.

Flaring combustion efficiency update

Global flaring estimates are based on reported data from the World Bank's Global Gas Flaring Reduction Partnership using data gathered and made accessible by the National Oceanic and Atmospheric Administration (NOAA) and the Payne Institute (World Bank, 2021). Contributions to country total production are binned by supply type (unconventional onshore, conventional onshore and offshore) and production start-up year using Rystad Energy UCube designations. Flaring design standards, API 521 and API 537, were utilised to guidance flare stack sizing assuming best-case design and optimal flare parameters during early production time (API, 2014; API, 2017).

Combustion efficiencies can reduce as a result of lower production rates, high and variable winds, and poor maintenance resulting from lack of regulatory policy, enforcement or company policy (Johnson, 2001; Kostiuk, 2004). The impact of wind speed was incorporated using NASA's Prediction of Worldwide Energy Resources (POWER) Meterology Data Access Viewer (NASA, 2021). Onshore wind speeds were assessed at 10m and offshore wind speeds at 50m to reflect closest height of flare stacks in actual facility design. Wind speed variability and its impact on combustion efficiency was incorporated corresponding to the location of production.

Flare volume operatorship were segregated by company type: Majors (ExxonMobil, Chevron, BP, Royal Dutch Shell, Eni SpA, TotalEnergies, and ConocoPhillips), National Oil Companies (NOCs) and Other (e.g. Independent, Private Equity) utilising operatorship assessment from Rystad Energy UCube. Maintenance levels to improve flaring combustion efficiencies were applied separately by company type assuming that more scrutiny from investors and the public is placed on the Majors as compared to NOCs or Other.

The World Bank's Worldwide Governance Indicators database (2021) was used as the basis to assess the general strength of regulatory oversight. Countries with stronger flaring regulation and strong regulatory oversight were calibrated assuming companies were mandated to quickly inspect and repair any malfunctioning or poor performing flare sites. Countries with weak flaring regulation and low levels of oversight were assumed to perform little to no additional maintenance.

Carbon dioxide and methane emissions are further calibrated to the local hydrocarbon content using the IEA's World Supply Model. Carbon dioxide equivalent emissions from the combustion of the hydrocarbon fluid streams are estimated in accordance with IPCC (2006) recommended values. One tonne of methane released is assumed to be equal to 30 tonnes of CO2-eq, based on the 100 year global warming potential.

8 Investment

Investment in fuel supply and the power sector

Investment is measured as the ongoing capital expenditures in fuel production and power generation capacity, as well as infrastructure. Projections of investment requirements by scenario are derived from the WEM energy supply and demand modules.

The calculation of the investment requirements for power generation and fuel supply involved the following steps for each region:

- New capacity needs for production, transportation and (where appropriate) transformation were calculated on the basis of projected demand trends, future supply required, estimated rates of retirement of the existing supply infrastructure and decline rates for oil and gas production.
- Unit capital cost estimates were compiled for each component in the supply chain. These costs were then adjusted for each year of the projection period using projected rates of change based on a detailed analysis of the potential for technology-driven cost reductions and on country-specific factors.
- Incremental capacity needs were multiplied by unit costs to yield the amount of investment needed as if the assets were constructed and became operational on an overnight basis.
- Finally, using technology and country/region-specific spending profiles, overnight investment needs were then distributed uniformly across construction lead times estimated for each asset, what we refer to as 'investment spending'.

The estimates of investment in the current decade take account of projects that have already been decided and expenditures that are already ongoing. This approach based on capital spending can differ across supply areas. For some sectors, such as power generation, the investment is spread out from the year in which a new plant or upgrade of an existing one begins its construction to the year in which it becomes operational. For other sources, such as upstream oil and gas and liquefied natural gas (LNG) projects, investment reflects the capital spending profiles typically incurred as production from a new source ramps up or to maintain output from an existing asset.

For the purposes of this study, investment is defined as capital expenditure only. It does not include spending that is usually classified as operations, maintenance, or spending devoted to servicing financing costs.

Short-term oil and natural gas upstream investment

Projections of upstream investment are based on a combination of bottom-up and top-down approaches. The former involves a detailed analysis of the plans and prospects for oil and gas industry investment in the future, with the aim of determining how much the industry is planning to invest in response to current prices and to the need for new capacity and of assessing the resulting additions to production capacity.

This analysis is based on a survey of the capital-spending programmes of over 80 leading upstream oil and gas companies (national and international companies and pure exploration and production companies), covering actual capital spending from 2000 to 2020 and their plans or forecasts of upcoming spending when available. Companies were selected on the basis of their size as measured by their production and reserves, though geographical spread and data availability also played a role. The surveyed companies account for over three-quarters of world oil and gas production. Total industry investment was calculated by adjusting upwards the spending of the companies, according to their share of world oil and gas production for each year. Data was obtained from companies' annual and financial reports, corporate presentations, press reports, trade publications and direct contacts in the industry.

Table 11: Sub-sectors and assets included in fuel supply investment

Sub-Sector	Assets
Oil and Gas	Upstream oil Upstream gas Midstream oil (pipelines) Midstream gas (pipelines and LNG) Refining (greenfield) Refining (upgrade and maintenance)
Coal supply	Coal mining Coal transportation
Low-emissions fuels	Biogases Liquid biofuels Hydrogen and hydrogen-based fuels production Hydrogen infrastructure

Long-term investment in fuel supply

Projections of long-term oil, gas, coal and low-emissions fuels investment requirements are generated in the respective supply-side modules. The level of investment is set to meet the level of demand projected in a given country, region and year. The methodology establishes a direct link over time between new production capacity brought on stream, the cash flow generated and the investments required. The cost of new capacity is estimated from a set of variables: size of the reserves, degree of depletion, location type of resource, technology employed, technology learning, and underlying assumptions for cost changes (which are a function of oil prices in the oil and gas supply-side modules). A more detailed projection was made for investments associated with hydrogen-based supply, including production of low-carbon hydrogen from electrolysis, fossil fuels (fitted with carbon capture utilisation and storage [CCUS] and infrastructure).

Power sector investment

Large investments in the power sector will be needed over the Outlook period to meet rising electricity demand, achieve decarbonisation goals and to replace or refurbish obsolete generating assets and network infrastructure. The overnight investments in generating assets are a straightforward calculation multiplying the capital cost ($/kW) for each generating technology by the corresponding capacity additions for each modelled region/country. Investment outlays are then spread over time based on spending profiles that begin at the start of construction and finish when an asset becomes operational.

The capital costs assumed in the power generation sector are based on a review of the latest country data available and on assumptions of their evolution over the projection period. They represent overnight costs for all technologies. For renewable sources and for plants fitted with CCUS facilities, the projected investment costs result from the various levels of deployment in the different scenarios. Indicative overnight costs and other relevant investment assumptions for all technologies by region may be found on the WEO model documentation page (http://www.iea.org/weo/weomodel/). For investment in transmission and distribution networks, please refer to section 4.3.

Table 12: Sub-sectors and assets included in power sector investment

Sub-Sector	Assets
Fossil-fuel based power generation	Coal-fired power Coal-fired power with CCUS Gas-fired power Gas-fired power with CCUS Oil-fired power
Nuclear power generation	Nuclear power plants (greenfield) Refurbishments and upgrades for long-term operations
Renewable power generation	Bioenergy Hydropower Wind (onshore and offshore) Geothermal Solar PV (utility-scale; residential, commercial and other distributed) Solar thermal Marine
Electricity grids	Transmission Distribution Public EV chargers
Battery storage	Utility-scale and buildings

Demand-side investments

Demand-side investments are consumer outlays for the purchase of end-use equipment. Ongoing spending associated is assumed to occur in the same year as when assets become operational. For efficiency, this does not include all of the spending, only the amount that is spent (including taxes and freight costs) to procure equipment that is more efficient than a baseline. The investment cost includes labour costs that are directly related to an installation, while additional costs can arise from administrative procedures, legal protection and border clearances, which are also included in the cost estimate. In other words, this calculation reflects the additional amount that consumers have to pay for higher energy efficiency over the projection period.

Across the WEM regions and for each end-use sector (industry, transport and buildings), the investment needed to move to greater efficiency levels have been analysed. The analysis is based on investment cost, stock turnover and the economic return required across sub-sectors in industry, across modes of transport and across end-uses in buildings. For example, in the road transport sector, the costs of efficiency improvements and of a switch to alternative fuel vehicles are used as an input to the model to determine each option’s cost-competitiveness. Based on the outcome of this analysis, the investment needs are then determined by multiplying the number of vehicles sold in each year by the costs of each vehicle.

In addition to energy efficiency, end-use investments include direct use of renewables, electric vehicles, electrification in buildings/industry, use of hydrogen and hydrogen-based fuels, and CCUS in industry.

Table 13: Sub-sectors and assets included in end-use energy investment

Sector	Sub-sector
Buildings	Energy efficiency (including building envelopes and retrofits) Electrification Renewables use Hydrogen-based use
Industry	Energy efficiency Electrification Renewables use CCUS Hydrogen-based use Fossil fuel-based industrial facilities
Transport	Energy efficiency of road transport Electrification of road transport and international marine transport Hydrogen and hydrogen-based road transport and shipping
Other	Direct air carbon capture and storage

Demand model outputs include the additional annual capital needs for each region and end-use sector. The impact of the energy savings on consumers' bills is also analysed. The sectoral end-user prices (including taxes) have been used to assess the overall impact of the policies on consumers over time. The results also include the impact on main importing countries.

Financing for investments

Sources of finance

Building upon analysis carried out in the Financing Clean Energy Transitions in Emerging and Developing Economies report, a more detailed assessment of the sources of finance associated with investments was carried out. While project developers act as the primary actors investing in energy assets, their success depends on a having robust inter-connected system of financial sources and intermediaries, diverse investment vehicles to facilitate flows and clear signals for action, based on profit expectations and risk profiles.

The sources of finance are characterised across four broad parameters:

- type of financing structure (off-balance sheet [project finance] or on-balance sheet [corporate finance]);
- type of provider (private or public [public finance institutions and state-owned enterprises]);
- type of instrument (according to capital structure - debt or equity);
- origin of provider (international or domestic sources).

For further details on estimation approach, please see the World Energy Investment Methodology Annex.

Cost of finance

The WEM incorporates differentiated assumptions on the cost of capital across regions within the supply, power and end-use sectors. For example, as some countries pursue efforts to minimise emissions from oil and gas operations in the APS, this increases their production costs relative to other producers and in many cases also involves additional financing costs (compared to those assumed in the STEPS). As explained in Section 4, a detailed analysis has been undertaken to reflect the reduction in financing costs for solar PV and wind across WEM countries/regions. Investment decisions in energy efficiency reflect the estimates for the prevailing debt and equity finance costs faced by consumers (for residential buildings and vehicles), businesses in the real estate sector (for commercial buildings) and companies from different industrial sectors across WEM regions. Financing costs are expressed in pre-tax terms calculated using the weighted average cost of capital (WACC):

$$WACC\ (real,\ pre\text{-}tax) = \frac{1 + (C_e * w_e + C_d * w_d)}{(1 + inflation)} - 1$$

Where:

C_e = Cost of equity

C_d = Cost of debt

w_i = share of debt or equity in the capital structure

For sectors where prices and underlying contracts are largely denominated in international currencies (e.g. USD), as in the oil and gas industry, cost components were estimated using mature market risk-free rates adjusted for country and sectoral risks. For sectors where prices and underlying contracts are denominated in local currencies, such as in power and end-use, cost components were estimated using local market risk-free rates adjusted for country and sectoral risks. Nominal data are converted into real terms using the Fischer Equation. Estimating the WACC components for the different energy sectors reflects data from financial markets and academic literature, complemented by interviews with market experts and practitioners. In addition, differentiated WACCs for the power sector outlook include analysis of auction results and PPA pricing.

Emissions performance of investments

Measuring the performance and targeting of capital flows against the investment needs of long-term net zero emissions goals is a complex task. Some investments will unequivocally help to reduce emissions; others are sure to increase them. The scenarios reveal a large number of gradations: a large portion of investments go towards sectors, technologies and infrastructure that do not immediately deliver zero emissions energy or energy services, but do enable such investments or provide incremental emissions reductions; some of these investments can also deliver zero emissions energy over time, but are contingent on actions elsewhere in the system, notably those concerned with decarbonising the power sector. To illustrate, WEO-2021 divided the total investment requirement in the scenarios into four categories:

- Low emissions: Investments that provide zero emissions (or very low emissions) energy or energy services, regardless of how the energy system evolves.
- Contingent: Investments that could provide or enable zero emissions energy or energy services but only with changes elsewhere in the energy system.
- Transition: Investments that provide emissions reductions but do not themselves deliver zero emissions energy or energy services.
- Unabated fossil fuels that do not enable emissions reductions: Investments in coal, oil and natural gas that do not provide any emissions reductions from today.

The allocation of investment in certain assets or technologies varies across regions and over time. For further details, please see Box 1.3.

9 Energy access

Defining modern energy access

There is no single internationally-accepted and internationally-adopted definition of modern energy access.

Yet significant commonality exists across definitions, including:

- Household access to a minimum level of electricity
- Household access to safer and more sustainable (i.e. minimum harmful effects on health and the environment as possible) cooking and heating fuels and stoves
- Access to modern energy that enables productive economic activity, e.g. mechanical power for agriculture, textile and other industries
- Access to modern energy for public services, e.g. electricity for health facilities, schools and street lighting

All of these elements are crucial to economic and social development, as are a number of related issues that are sometimes referred to collectively as "quality of supply", such as technical availability, adequacy, reliability, convenience, safety and affordability.

The data and projections presented in the WEO focus on two elements of energy access: a household having access to electricity and to clean cooking facilities. The IEA defines energy access as "*a household having reliable and affordable access to both clean cooking facilities and to electricity, which is enough to supply a basic bundle of energy services initially, and with the level of service capable of growing over time*". This energy access definition serves as a benchmark to measure progress towards goal SDG 7.1 and as a metric for our forward-looking analysis.

Electricity access entails a household having initial access to sufficient electricity to power a basic bundle of energy services – at a minimum, several lightbulbs, phone charging, a radio and potentially a fan or television – with the level of service capable of growing over time. In our projections, the average household who has gained access has enough electricity to power four lightbulbs operating at five hours per day, one refrigerator, a fan operating 6 hours per day, a mobile phone charger and a television operating 4 hours per day, which equates to an annual electricity consumption of 1 250 kWh per household with standard appliances, and 420 kWh with efficient appliances. This service-level definition cannot be applied to the measurement of actual data simply because the level of data required does not exist in a large number of cases. As a result, our electricity access databases focus on a simpler binary measure of those that have a connection to an electricity grid, or have a renewable off- or mini-grid connection of sufficient capacity to deliver the minimum bundle of energy services mentioned above.

Access to clean cooking facilities means access to (and primary use of) modern fuels and technologies, including natural gas, liquefied petroleum gas (LPG), electricity and biogas, or improved biomass cookstoves (ICS) that have considerably lower emissions and higher efficiencies than traditional three-stone fires for cooking. Currently, very few ICS models attain this lower emissions target, particularly under real-world cooking conditions. Therefore, our clean cooking access database refers to households that rely primarily on fuels other than biomass (such as fuelwood, charcoal, tree leaves, crop residues and animal dung), coal or kerosene for cooking. For our projections, only the most improved biomass cookstoves that deliver significant improvements are considered as contributing to energy access. The main sources are the World Health Organisation (WHO) Household Energy Database and the IEA Energy Balances.

Outlook for modern energy access

Outlook for electricity access

The IEA's electricity access database[17] provides valuable information about the current electrification rates in a large number of countries. In order to provide an outlook for electricity access in the next decades, a model able to generate projections of electrification rates by region has been developed. The projections are based on an econometric panel model that regresses historic electrification rates of different countries over many variables, to test their level of significance. Variables that were determined statistically significant and consequently included in the equations are per-capita income, demographic growth, urbanisation, fuel prices, level of subsidies, technological advances, energy consumption, and energy access programmes.

Outlook for clean cooking access

Our baseline data on the traditional use of biomass for cooking is based on the World Health Organization's (WHO) Global Health Observatory estimates of reliance on solid fuels.[18] To provide an outlook for the number of people relying on the traditional use of biomass in the next decades, a regional model was developed under different assumptions. Reliance on biomass rates of different countries is projected using an econometric panel model estimated from a historical time series. Variables that were determined statistically significant and consequently included in the equations are per-capita income, demographic growth, urbanisation level, level of prices of alternative modern fuels, subsidies to alternative modern fuel consumption, technological advances and clean cooking programmes.

For more detail on the energy access analysis and methodology see also the dedicated section on the WEO website: https://www.iea.org/topics/energy-access.

Affordability of basic electricity services

For *WEO-2020*, a new analysis was conducted on the impact of the Covid-19 pandemic on the affordability of basic electricity services for households in Africa and Developing Asia. This analysis has been updated for the WEO-2021, where also pre-pandemic as well cooking LPG affordability have been estimated. Using poverty data from Lakner et al. (2021), as well as country electricity and LPG prices, we analysed the extent to which poverty and the impact of Covid-19 could bring about energy affordability if households are unable to afford basic electricity services.

We considered two bundles of electricity services: an essential bundle (including four lightbulbs operating four hours per day, a fan three hours per day and a television two hours per day; equating to 500 kilowatt-hours (kWh) per household per year with standard appliances), and an extended bundle (including the essential bundle plus one refrigerator, and double hours for the fan and the television; equating to 1 250 kWh per household per year with standard appliances). The number of people at risk of losing basic electricity services was estimated by combining data on the costs of these bundles in different countries with data on the number of additional households pushed across different poverty lines ($1.90/day, $3.20/day or $5.50/day) as a result of the crisis. We considered a household at risk of losing ability to pay when it represents over 5% of the household spending.

[17] https://www.iea.org/reports/sdg7-data-and-projections/access-to-electricity

[18] For more information, see www.who.int/gho/phe/indoor_air_pollution/en/index.html

10 Employment

The IEA added an energy employment module to the World Energy model in 2020, and now covers 40 different energy subsectors in 26 regions under different IEA scenarios. The scope is also ongoing further expansion in the coming year. The model currently analyses:

- The number of people employed in major energy supply and end-use sectors, including electricity, oil, natural gas, coal and biofuels.
- The number of job losses and gains in the energy and related sectors as a direct product of shifting investments, production, and operation of energy assets

The model estimates how many jobs are created or maintained based on the current asset base and the annual investments in new infrastructure or spending on certain goods or energy commodities. This technical annex describes:

- How energy employment is defined and the scope of calculations
- The methodology used to estimate energy employment under different scenarios

Definition and scope of employment

Employment assessments classify job creation impacts of projects in the following schema:

- **Direct**: Jobs created to deliver a final project or product.
- **Indirect**: Supply chain jobs created to provide inputs to a final project or product.
- **Induced**: Jobs created by wages earned from the projects and spent in other parts of the economy, thereby creating additional jobs.
- **Cost savings re-spend**: Jobs created by reduced customer energy costs being spent elsewhere in an economy. These jobs, also referred to as second-order jobs, can also be negative, if, for example, the cost of energy were to rise for consumers in the wider economy, leading to a reduction in spending in other parts of an economy.

Our employment analysis includes all direct jobs and the indirect jobs from suppliers providing immediate inputs to the energy sector. Induced jobs and jobs that may be created from re-spend are not included. This sets a clear boundary around the jobs that the upfront investment would pay for to deliver the project.

Jobs are normalised to full-time employment (FTE) for consistent accounting. An FTE job represents one person's work for one year at regulated norms (e.g. 40 hours a week for 52 weeks a year, excluding holidays). Two separate, six-month jobs would be counted as one FTE job.

Jobs are reported as either job-years or jobs. The "job-years" term is used to report the cumulative years of FTE over a period of time. The term "jobs" is used to report employment during a single year or an average over a period. The use of job-years or jobs does not imply anything about the permanency of the jobs.

Where possible, the jobs created are classified as:

- **Manufacturing**: Jobs producing direct inputs to an energy project.
- **Construction:** Jobs installing, constructing and commissioning energy projects.
- **Operations and maintenance** (O&M)**:** All ongoing jobs required to support the proper operation of an energy project.

Manufacturing and construction jobs are calculated over the lifetime of the production and construction phase of projects, while O&M jobs are calculated over the usable lifetime of the energy project.

Estimating employment

Our model uses energy investment and spending data, production data, and existing assets as the basis to estimate global employment. These indices are gathered across 40 different sub-sectors (e.g. solar power generation, biofuel production, natural gas development, EV manufacturing) and then multiplied by employment multipliers calibrated for each of these indices. The database of multipliers was compiled based on energy sector specific wage data, project cost structure, and calibrated against official government statistics where available. When specific sub-sectoral government statistics were not available, literature review and industry engagement were used as reference calibration points. The method to produce the full subset of multipliers is described below:

- Gathering employment and wage data for each subsector within each region, where available.
- Where unavailable, using generalised wage data for the associated region and economic activity to calculate appropriate multipliers
- Estimating multipliers for regions and technology types where insufficient primary estimates exist.

Gathering multiplier input data

Measures use one of two types of multipliers: those whose denominators are in million US dollars invested, and those whose denominators are in million US dollars spent on final goods. The denominator used is dependent on the nature of the measure, and in particular whether it aims to encourage investment in assets or consumer purchases.

We focus on new employment multipliers. These give the number of new jobs created by an incremental investment of $1 million or an increase of $1 million in final goods. They differ from active employment multipliers, expressed as jobs per million dollars of existing revenue, which more closely reflect O&M employment.

The primary sources used include:

- Wage data, employment census and survey data.
- Calculated multipliers from legal financial filings that provide information on employment and revenue, cost breakdowns for projects and average wages.
- Academic, intergovernmental research and modelling results.
- Individual company and industry group estimates.

Government surveys of businesses were prioritised, when available with sufficient detail, to support the subsectoral analysis (e.g. the North American Industry Classification System (NAICS) codes or the European Nomenclature of Economic Activities (NACE) codes). Many of these codes provide detailed data at the 6-digit code level (e.g. manufacturers of pumps and compressors). Where unavailable, higher-level NAICS or equivalent codes were used to guide our multipliers (e.g. the workforce composition and wage data for electric vehicle chargers is likely not far off from the generalised data for electrical equipment manufacturing). These were used to filter out other multipliers that vary too far from the average.

Employment and financial information were extracted from the annual reports of major companies in each sector. Data for different years were used to estimate how changes in investment levels (derived from the IEA's *World Energy Investment 2021* report[19]) impacted changes in employment. This method could only be used for sectors with a high degree of consolidation in major firms that are publicly listed.

[19] https://www.iea.org/reports/world-energy-investment-2021.

Material from academic and industry sources was screened to ensure harmonised definitions and reference values were adjusted to adhere to the framework described. In other words, if there was insufficient information to make adjustments, sources that did not adhere to these definitions were removed. It is worth noting in particular that:

- Direct component manufacturing is often included in direct employment instead of indirect. Where possible, manufacturing jobs are reclassified as indirect, or have not made a distinction between direct and indirect jobs for that multiplier.
- Estimates of indirect jobs sometimes include jobs created to support the operation and maintenance of the project or equipment. These are reported separately to clarify that they are not paid for by the Covid-19 stimulus investment.
- Indirect sometimes includes jobs "supported" by the purchase where the equipment is a key enabler for another job, for example, automobile manufacturing is a key enabler for delivery and taxi driving jobs. These "supported" jobs are not included in our analysis.

Where values from these sources were unavailable, estimates were based on employment multipliers for similar technologies. Cost breakdowns for building new projects or the production of one unit were used to estimate how much of the million dollars spent went to labour or materials. Based on available wage information for subsectors, direct labour was calculated by dividing total labour cost contribution by average wages. For indirect multipliers, the amount spent on materials in the original project was multiplied by an average multiplier from direct supplier industries. If it was not possible to isolate primary supplier industries, or their multipliers were not available, multipliers were used from higher level NAIC codes as a proxy for the indirect labour multiplier.

Once these multipliers were assembled, historic values were adjusted to express them in 2020 US dollars. Weighted averages of the full list of associated references were taken, basing those on the relevant and rigour the source material, to control for outliers.

Multipliers were tested with companies within IEA's Energy Business Council, peer reviewers, experts from academia, industry groups and other international organisations (such as the International Monetary Fund and International Labour Organization).

Regional multipliers

Employment data is not available for all regions and so regional multipliers were constructed based on wage differences for the standard regions in the IEA World Energy Model (WEM).These regional multipliers were arrived at by a variety of means, but most were created through the use of wage adjustments. This process involved:

- **Identifying the cost contribution breakdown** for $1 million spent on new projects or products for regions with existing multipliers (e.g. 10% labour, 50% materials, 10% equipment costs). These breakdowns were derived using detailed manufacturer surveys, primarily from the US Annual Manufacturer's Survey data which provide information on the contribution to costs of average wages, labour and materials. Industry evaluation and heuristics were used to confirm breakdowns or provide more granular breakdowns for specific technology types.
- **Adapting the cost contribution breakdown to each region**, taking specific account of how differences in wages and material costs shift the relative shares of labour and material. Average wages and basic material costs were indexed on the basis of US costs, and these were applied to the labour and material costs for a $1 million project or purchase to calculate how much that same purchase would cost to produce in a low-wage economy. For example, in the United States $1 million spent on batteries represents roughly $140 000 for labour costs, but when adjusting for low-wage economies, producing the same amount of batteries would only be $3 000 in labour costs. We then need to adjust the amount of batteries back up to arrive at a

$1 million purchase in low-wage economies. If labour is much cheaper than project inputs, then the percent contributions of labour and material costs shift in low-wage economies. We provide an example calculation below in Table 1.1. We utilised local wages, average cost differential of input materials, share of imports in production and the costs of those imports to arrive at adjusted cost contribution breakdowns for various regions. These inputs were derived from the global balance of trade in value added. In lower cost economies, the labour index is lower than the material cost index, resulting in the proportion of total project or product cost accounted for by labour costs going down, and the proportion of total cost accounted for by input materials going up.

- **Finding average wages for relevant jobs in a region** by using national average salary information specific to a subsector. Where information on wages specific to a subsector was not available, average wages from salary reporting websites were used, splitting the labour costs to distinguish between those associated with production and manufacturing and those associated with overheads (e.g. research and development, procurement and marketing). To calibrate the correct weighting of various salary types, average wages were used for generalised sectors (e.g. manufacturing of durable goods, construction) to provide guidance. For technologies that have a relatively globalised market (e.g. solar photovoltaic panels), a global average of salaries is assumed based on each countries' share of total production. This provides an indirect multiplier that can be applied to all regions.
- **Calculating jobs per million dollars** for the expenditure by dividing the portion spent on salaries by average salaries. The indirect multiplier for advanced economies was used as a basis for indirect jobs, and the rectification multiplier for each country was applied to calculate indirect jobs. Since inputs for industries can be diverse across the entire economy, the rectification multiplier, which uses generalised wages, reflects economy-wide cost differences and does not need to apply specific wage types to arrive at more exact direct jobs numbers.

Table A.1 Example calculation of labour contributions in different regions

	Base ($ million)	Cost adjustment index	Low-wage economies ($ million)	Low-wage economies, rescaled to $1 million
Labour	0.15	0.1	0.15*0.1= 0.015	(0.15+0.5)/(0.015+0.3)*0.015 = 0.031
Materials	0.5	0.6	0.50*0.6= 0.3	(0.15+0.5)/(0.015+0.3)*0.3 = 0.62

Calculating total employment

The final employment multipliers were integrated with the WEM by applying the multipliers to the appropriate sector and regional investments.

In all cases, the multipliers were applied to investment or changes in investment, not revenues or total assets, to calculate the number of jobs created by or necessary to support the level of new investment. When providing jobs within a single year, we considered for how long and when an investment or purchase creates those jobs. For instance, investment in a new hydroelectric dam would create some jobs in the planning and preparation phase prior to the investment: when financial close occurs, these jobs disappear, but construction and equipment manufacturing jobs are created; when construction is completed, these jobs disappear, but O&M jobs begin. Jobs are assigned to the relevant years to understand total employment on an annual basis.

Existing jobs

Existing jobs include both O&M jobs associated with the existing asset base and jobs supporting the investments made in the preceding years:

- O&M jobs associated with the existing asset base were estimated using employment surveys and census data, annual reports of major companies, academic research, and multipliers derived by estimating the number of employees associated with different facilities and scaling them up in line with total facilities globally. There were substantial gaps in current employment data, and these were estimated and these estimates were tested with experts.
- Jobs supporting the investments made in previous years were calculated by applying the multipliers to new investment in the immediately preceding years, using data on new investment from the IEA's *World Energy Investment 2021* report. This is used to estimate how many manufacturing and construction jobs were supported by projects underway or in the pipeline.
- The two totals were added together to produce the total jobs numbers where presented in IEA reports.

New jobs

Multipliers were applied to the level of investment included in the plan for each year to calculate total jobs in future years. Figures for the jobs created take account of the timing delays between investment and job creation for each subsector. They also take account of minimum lead times for projects already through the feasibility study phase to move from plan to financial close.

Investment numbers were produced for each region and subsector, and the corresponding multipliers were applied for each region. For investments in which figures for manufacturing, construction and O&M jobs are available, a breakdown was produced of the types of skills needed for those jobs and the regions where those jobs would be created. For technologies with a highly globalised supply chain, manufacturing jobs are divided across regions according to current production capacities. For technologies that have very localised production, such as building materials and biofuels, all manufacturing jobs were assumed to be created locally.

Jobs lost

Jobs lost include jobs associated with a slowdown in building new projects, those decreased due to declining revenues and production, and those lost due to closure of certain fossil fuel assets. Multipliers denominated in jobs per millions invested were applied to the decline in the level of investment to calculate how many jobs in construction and manufacturing are likely to have been lost in the long-run due to structurally decreased demand if investment levels are not bolstered. Different multipliers were used based on declining production volumes to assess the impacts and sensitivity of sectors in decline to losing existing employment based on declining output. Finally, a last set of O&M multipliers is based on the total asset base for the sector (e.g. number of coal power plants, total asset base of oil and gas pipelines). These estimates are summed together then subtracted from total employment in the base year, to produce job loss figures.

11 Assessing recovery plans

The IEA launched its Sustainable Recovery Tracker to evaluate the impact of sustainable recovery policies enacted by governments in response to the Covid-19 crisis:

- Collects the amount of government spending directed toward sustainable recovery measures specified in the IEA's Sustainable Recovery Plan that are additional to already-committed public spending;
- Estimates the amount of private spending mobilised thanks to recovery plans and policymaking; and

This analysis relies on collecting and analysing sustainable recovery policies from around the world, defined in relation to measures highlighted in the IEA's Sustainable Recovery Plan. It also estimates of the ability of government financial commitment to "crowd-in" larger amounts of private capital for investment in a specific sector or project, or so-called "mobilisation factors". While this analysis sits separately from the WEO, it relies heavily on WEO modelling and data schematisations, and the findings on government expenditure and its impacts were featured in WEO 2021, and will feature in future WEO publications.

In the following methodology, we describe the analysis involved in the development of the Tracker, focusing on the following analytical steps:

- The identification and collection of national sustainable recovery policies;
- The assessment of their impact on overall clean energy investment, based on public to private spending mobilisation factors; and

Sustainable Recovery policy identification and collection

Definition and Scope of sustainable recovery policies

Sustainable recovery policies are defined as policies driving spending on clean energy measures in the IEA Sustainable recovery Plan, a three-year energy sector global spending programme recommended for inclusion in Covid-19 related government recovery plans. A full implementation of the Plan in the framework of 2021-2023 government recovery efforts would spur economic growth, create millions of jobs and put global emissions into structural decline, ensuring the world is on track to meeting the Paris Agreement goals and Sustainable Development goals on air pollution, clean-cooking and electricity access.

Common sustainable recovery policies include consumer or producer subsidies to develop electric vehicle markets, direct spending or public-Private Partnership for building low-carbon and efficient transport infrastructures, grants for emerging energy technology pilot programmes, or tax incentives for energy-efficient building renovations.

Quantitative estimates in the Sustainable Recovery Tracker are based on national-level clean energy sector policies enacted by governments from the second quarter of 2020 as part of Covid-19 related recovery measures, and directed toward long-term projects and measures to boost economic growth.

The following type of spending are considered in the analysis

- **Total fiscal support:** all government spending disbursed from 2020 in response to the COVID-19 crisis, in the form of additional spending and/or forgone revenue, as per the IMF Fiscal Monitor definition. This includes short-term economic relief payments to citizens and firms to weather the effects of the pandemic.
- **Economic recovery spending:** government spending directed to long-term projects and measures to boost growth, a subset of total fiscal support. Examples include infrastructure projects like roads, broadband internet, public housing upgrades, incentives for business improvements etc. Many governments tended to turn to these long-term perspective policies from the second quarter of 2020, after having precedent concentrated on emergency economic and health support. This does not include economic relief payments to citizens and firms; and only includes spending that is directed specifically to new investments.
- **Government spending on sustainable recovery measures**: government spending targeting measures highlighted in the IEA Sustainable Recovery Plan, a subset of economic recovery spending. This includes consumer or producer subsidies, tax breaks, public procurement, loan guarantees, PPP contracts and other co-funding schemes favoured by governments. Only direct government fiscal spending from the second quarter of 2020 is considered, spending directed by regulators to state-owned enterprises (SOEs) or publicly regulated entities being set aside.
- **Total mobilised sustainable recovery spending**: all public and private spending on measures highlighted in the IEA Sustainable Recovery Plan mobilised by the above mentioned government spending. Spending by SOEs is taken into account in this total.

The last two categories, which encompass government and total mobilised sustainable recovery spending were compared, on a sectoral and regional basis, to the levels recommended in the Sustainable Recovery Plan in the six key sectors: low-carbon electricity, electricity networks, low-carbon and efficient transport, energy efficient buildings and industry, cleaner fuels and emerging low-carbon technologies.

Only additional recovery spending aimed at creating new assets or extending the life of existing low-carbon infrastructure is considered. Accordingly, liquidity measures for energy companies or energy intensive industries are not directly incorporated, since they do not support additional low-carbon activities. However, as supporting energy firms through the pandemic preserves their ability to attract investment, this benefit was captured in calibrating sectoral factors assessing mobilised private spending, together with policies generally ameliorating the investment environment (see Section 1.2, Assessing mobilisation factors).

Collection process

The IEA independently collects recovery policies, in cooperation with its members, as well as G20 members.

The full list of policies considered in the Tracker, including budget information, is available on the IEA Policies and Measures (PAMS) Database, a unique repository that has aggregated energy policies over the last 20 years, bringing together data from the IEA Energy Efficiency Database, the Addressing Climate Change database, and the Building Energy Efficiency Policies (BEEP) database, the IEA/IRENA Renewable Energy Policies and Measures Database, along with information on CCUS and methane abatement policies. These policy records include concise summaries of the policy, links to the original source, and relevant tagging for policy type, technologies and sectors.

In addition to the 10 840 policies included in the database, over 800 sustainable recovery policies can therefore be accessed online, covering over 50 countries. Government sustainable recovery spending is recorded and attributed to timelines officially announced, according to available information. Total mobilised sustainable recovery spending is afterwards spread evenly across all announced years. Each budget item is also tagged with the sustainable recovery measure it targets.

Assessing the impact on overall clean energy investment

The impact of government recovery spending on overall investment was assessed using mobilisation factors per sector and geography. This assessment is separate from the total investment numbers cited in the WEO and WEI reports, which instead rely on the modelling and data recording approaches described previously in this modelling documentation. The emphasis of this modelling is to assess how much of the additional investment is supported by government spending, within the known constraints of this kind of attribution exercise

The ability for government spending to crowd-in private investment varies greatly across contexts, and depends on many different factors, ranging from the type, scale and temporality of the fiscal intervention to aspects inherent to local economic and financial contexts and, increasingly, global commercial trends.

The approach chosen seeks to approximate this mobilisation effect based on a limited number of known factors, partly drawn from historical trends. The evaluation will be complemented and enhanced as data becomes available, notably on the evolution of the economic crisis in different regions as well as on the ex-post assessments of Covid-19 recovery policies. The IEA aims at refining this modelling approach, in particular to try and assess better how a specific policy type improves efficacy of public dollars mobilised and calibrating the approach based on real investment seen in the field.

Assessing mobilisation factors

Past mobilisation factors (one per technology per region) were derived from historic levels of investment and government support, drawing from the IEA's energy investment database. These historic mobilisation factors were then calibrated to reflect changing investment conditions. The IEA used a series of indices, pulled from IEA data or global financial sources, to help calibrate the mobilisation factors. These indices can use raw data points (e.g GDP growth), Binary variable (e.g. is this supporting policy available in the region), and expert rating variables (e.g. on a scale of 1-5, how mature is the XX market in region YY). The indices used for this calibration include:

- **Macroeconomic factors**: GDP growth rate, cost of capital, credit risk rating of the country/region;
- **Energy industry health**: whether liquidity support was made available, maturity of the market for the specific clean energy measure in question
- **Supporting policy environment**: the presence of supporting non-fiscal policies (e.g. priority parking for electric vehicles), market or pricing mechanisms supportive of deployment (e.g. special all-electric utility rates), degree of administrative support/burden (e.g. typical timelines for permitting approval), effectiveness/maturity of policy mechanisms deployed (e.g. how many years has the policy been in place)
- **Cost-effectiveness**: payback period for the measures or cost-competitiveness against alternatives (e.g. LCOEs)

Historic mobilisation factors were therefore increased or decreased in line with the estimated amelioration or deterioration of regional investment environment between past years (2015-19) and 2021, based on our internal evaluation of how sensitive particular technologies are to these conditions. The coherence of mobilisation factors is eventually cross-checked between regions and technologies, as well as with existing field research from IEA experts and policy assessments done by countries, to detect and analyse differences with country estimates.

Global averages for mobilisation factors (2021-23) across category of sustainable recovery measures

Innovation	2.2	1.5
Buildings	10.3	6.7
Industry	8.9	4.7
Transport	5.3	4.1
Electricity	5.9	4.9

Notes:

In general, mobilisation factors tend to be lower in emerging and developing economies because of the strong reliance of government signals and direct procurement to mobilise investment. A higher level of SOE participation in the economy means private sector action mobilised through direct incentives may be lower, but governments can direct more funding through SOEs in many sectors, which is accounted for in the tracker separately from the mobilisation factor approach.

Electricity mobilisation factors in EMDEs are on average lower to reflect SOE dominance in this sector, which often limits private sector participation. Regulatory interventions to orientate spending is therefore preferred by authorities to direct government incentives in these cases. The tracker therefore considers increased spending announced via regulatory approvals and utility plans, but does not use mobilisation factors, instead just counting planned spending as is.

Transport mobilisation factors are higher for consumer oriented products (e.g. electric vehicles and electric 2-3 wheelers), mid-to-low range for commercial vehicles and other fleets, and very low for public transport, where government direct spending is a commonly used incentive.

Innovation mobilisation factors are overall low over the short-term (2021-2023) driven by co-funding schemes that have high government upfront participation, that crowd in more private investment in the future, and with provisions to refund of this public contribution later. In the medium-term and long-term however, mobilisation factors are higher as risk pay-back materialises, initially for more mature technologies, and then for earlier stage R&D.

Ensuring additionality to existing clean energy investment

The IEA Sustainable Recovery Tracker effectively aims at identifying additional levels of investments on top of the IEA's Stated Policies Scenario, which is updated annually to consider the effect of newly announced policies on the trajectory for energy demand.

While difficult to disentangle and produce a clear counterfactual, the Tracker identifies which portion of the public spending contributes to elevating investment over previous IEA projections for future investment. Some cases are clear, such as a new innovation fund or direct government spending on energy efficiency in public buildings voted in the fall of 2020, both explicitly tied to a national recovery plan. Some of the mobilised sustainable recovery spending is however not always additive to previous projections, due to different effects:

- Some of this spending effectively compensates for the decrease in spending, thus bringing future investment levels back up to historic levels.
- Part of the public spending inevitably goes to support projects already in the pipeline that would have occurred without the support (for instance, new EV purchase that would have happened without a subsidy)

The calibration of our mobilisation factors considers these effects as possible. Examples include: extension of tax credits for projects already in the pipeline that may now be eligible or incentives electric vehicles, which may go to people already planning to buy EVs or may bring deferred car purchases forward a few years, firming up investments delayed by Covid-19.

We also recognise government spending, even if going toward projects that would happen anyway or firming up investment drops, actually keeps firms healthy, poised for future expansion, and incentives for projects already moving ahead can makes firms more profitable, thereby improving their ability to attract investment in the future. This type of spending is short-term oriented, and does little to move more investment in the near-term, but has effects for the industry in the future, which we factored into projections that will be forthcoming in IEA reports.

Determining implementation timelines

Many sustainable recovery policies are targeting projects or investments that will not materialise in the near-term (e.g. offshore wind projects with long lead times, or CCUS pilots). It also considers how some spending is meant to lay the groundwork for increased long-term private sector spending or involvement (e.g. port and fuelling infrastructure, and support to innovation).The IEA Sustainable Recovery Tracker determines when the total sustainable recovery spending mobilised actually materialised-in-the-ground by taking into account three specific steps and associated delays:

- average time from policy announcement to disbursement for viable projects (from policy assessments conducted at the IEA);
- average time from financial closure to effective operation (from our World Energy Investment data);
- average delay for certain government supports (e.g. supporting infrastructure, innovation funding, research, market reforms) to materialise their impacts (estimated based on large infrastructure project timelines),

The first two are reflected by delaying the year when those investments come on relative to the year the funding is announced. The last is by increasing the private spending mobilisation factor for subsequent years. While the latter does not prominently effect estimates in the tracker (only covers 2021-23), it will figure in forthcoming IEA publications and tracking.

Annex 1: *WEM* terminology

A1.1 Definitions

Advanced bioenergy: Sustainable fuels produced from non-food crop feedstocks, which are capable of delivering significant lifecycle greenhouse gas emissions savings compared with fossil fuel alternatives, and which do not directly compete with food and feed crops for agricultural land or cause adverse sustainability impacts. This definition differs from the one used for "advanced biofuels" in US legislation, which is based on a minimum 50% lifecycle greenhouse gas reduction and which, therefore, includes sugar cane ethanol.

Agriculture: Includes all energy used on farms, in forestry and for fishing.

Agriculture, forestry and other land use (AFOLU) emissions: Includes greenhouse gas emissions from agriculture, forestry and other land use.

Ammonia (NH_3): Is a compound of nitrogen and hydrogen. It can be used directly as a fuel in direct combustion processes, as well as in fuel cells or as a hydrogen carrier. To be a low emissions fuel, ammonia must be produced from low-carbon hydrogen, the nitrogen separated via the Haber process with electricity generated from low-carbon sources.

Aviation: This transport mode includes both domestic and international flights and their use of aviation fuels. Domestic aviation covers flights that depart and land in the same country; flights for military purposes are included. International aviation includes flights that land in a country other than the departure location.

Back-up generation capacity: Households and businesses connected to the main power grid may also have some form of back-up power generation capacity that, in the event of disruption, can provide electricity. Back-up generators are typically fuelled with diesel or gasoline. Capacity can be as little as a few kilowatts. Such capacity is distinct from mini-grid and off-grid systems that are not connected to a main power grid.

Battery storage: Energy storage technology that uses reversible chemical reactions to absorb and release electricity on demand.

Biodiesel: Diesel-equivalent, processed fuel made from the transesterification (a chemical process that converts triglycerides in oils) of vegetable oils and animal fats.

Bioenergy: Energy content in solid, liquid and gaseous products derived from biomass feedstocks and biogas. It includes solid bioenergy, liquid biofuels and biogases.

Biogas: A mixture of methane, CO_2 and small quantities of other gases produced by anaerobic digestion of organic matter in an oxygen-free environment.

Biogases: Include both biogas and biomethane.

Biomethane: Biomethane is a near-pure source of methane produced either by "upgrading" biogas (a process that removes any CO_2 and other contaminants present in the biogas) or through the gasification of solid biomass followed by methanation. It is also known as renewable natural gas.

Buildings: The buildings sector includes energy used in residential, commercial and institutional buildings and non-specified other. Building energy use includes space heating and cooling, water heating, lighting, appliances and cooking equipment.

Bunkers: Includes both international marine bunkers and international aviation bunkers.

Capacity credit: Proportion of the capacity that can be reliably expected to generate electricity during times of peak demand in the grid to which it is connected.

Carbon capture, utilisation and storage (CCUS): The process of capturing CO_2 emissions from fuel combustion, industrial processes or directly from the atmosphere. Captured CO_2 emissions can be stored in underground geological formations, onshore or offshore or used as an input or feedstock in manufacturing.

Carbon dioxide (CO_2): Is a gas consisting of one part carbon and two parts oxygen. It is an important greenhouse (heat-tapping) gas.

Clean energy: In *power*, clean energy includes: generation from renewable sources, nuclear and fossil fuels fitted with CCUS; battery storage; and electricity grids. In *efficiency*, clean energy includes energy efficiency in buildings, industry and transport, excluding aviation bunkers and domestic navigation. In *end-use* applications, clean energy includes: direct use of renewables; electric vehicles; electrification in buildings, industry and international marine transport; use of hydrogen and hydrogen-based fuels; CCUS in industry and direct air carbon capture and storage. In *fuel supply*, clean energy includes low emissions fuels liquid biofuels and biogases, low-carbon hydrogen and hydrogen-based fuels.

Clean cooking systems: Cooking solutions that release less harmful pollutants, are more efficient and environmentally sustainable than traditional cooking options that make use of solid biomass (such as a three-stone fire), coal or kerosene. This refers primarily to improved solid biomass cookstoves, biogas/biodigester systems, electric stoves, liquefied petroleum gas, natural gas or ethanol stoves.

Coal: Includes both primary coal (i.e. lignite, coking and steam coal) and derived fuels (e.g. 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.

Coalbed methane (CBM): Category of unconventional natural gas, which refers to methane found in coal seams.

Coal-to-gas (CTG): Process in which mined coal is first turned into syngas (a mixture of hydrogen and carbon monoxide) and then into synthetic methane.

Coal-to-liquids (CTL): Transformation of coal into liquid hydrocarbons. It can be achieved through either coal gasification into syngas (a mixture of hydrogen and carbon monoxide), combined using the Fischer-Tropsch or methanol-to-gasoline synthesis process to produce liquid fuels, or through the less developed direct-coal liquefaction technologies in which coal is directly reacted with hydrogen.

Coking coal: Type of coal that can be used for steel making (as a chemical reductant and a source of heat), where it produces coke capable of supporting a blast furnace charge. Coal of this quality is also commonly known as metallurgical coal.

Concentrating solar power (CSP): Solar thermal power generation technology that collects and concentrates sunlight to produce high temperature heat to generate electricity.

Conventional liquid biofuels: Fuels produced from food crop feedstocks. Commonly referred to as first generation biofuels and include sugar cane ethanol, starch-based ethanol, fatty acid methyl ester (FAME), straight vegetable oil (SVO) and hydrotreated vegetable oil (HVO) produced from palm, rapeseed or soybean oil.

Decomposition analysis: Statistical approach that decomposes an aggregate indicator to quantify the relative contribution of a set of pre-defined factors leading to a change in the aggregate indicator. The *World Energy Outlook* uses an additive index decomposition of the type Logarithmic Mean Divisia Index (LMDI).

Demand-side integration (DSI): Consists of two types of measures: actions that influence load shape such as energy efficiency and electrification; and actions that manage load such as demand-side response.

Demand-side response (DSR): Describes actions which can influence the load profile such as shifting the load curve in time without affecting total electricity demand, or load shedding such as interrupting demand for a short duration or adjusting the intensity of demand for a certain amount of time.

Direct air carbon capture, utilisation and storage (DACCUS): Technology to capture CO_2 from the atmosphere and permanently store it in deep geological formations or to be used in the production of fuels, chemicals, building materials or other products that use CO_2. When the CO_2 is geologically stored it is permanently removed from the atmosphere resulting in negative emissions.

Dispatchable generation: Refers to technologies whose power output can be readily controlled, i.e. increased to maximum rated capacity or decreased to zero, in order to match supply with demand.

Electricity demand: Defined as total gross electricity generation less own use generation, plus net trade (imports less exports), less transmission and distribution losses.

Electricity generation: 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.

End-use sectors: Includes industry (i.e. manufacturing, mining, chemical production, blast furnaces and coke ovens), transport, buildings (i.e. residential and services) and other (i.e. agriculture and other non-energy use).

Energy-related and industrial process CO_2 emissions: Carbon dioxide emissions from fuel combustion and from industrial processes. Note that this does not include fugitive emissions from fuels, flaring or CO_2 from transport and storage. Unless otherwise stated, CO_2 emissions in the *World Energy Outlook* refer to energy-related and industrial process CO_2 emissions.

Energy sector greenhouse gas (GHG) emissions: Energy-related and industrial process CO_2 emissions plus fugitive and vented methane (CH_4) and nitrous dioxide (N_2O) emissions from the energy and industry sectors.

Energy services: See useful energy.

Ethanol: Refers to bio-ethanol only. Ethanol is produced from fermenting any biomass high in carbohydrates. Currently, 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.

Fischer-Tropsch synthesis: Catalytic production process for the production of synthetic fuels. Natural gas, coal and biomass feedstocks can be used.

Fossil fuels: Include coal, natural gas, oil and peat.

Gases: Include natural gas, biogases, synthetic methane and hydrogen.

Gaseous fuels: Include natural gas, biogas, biomethane, hydrogen and synthetic methane.

Gas-to-liquids (GTL): Process featuring reaction of methane with oxygen or steam to produce syngas (a mixture of hydrogen and carbon monoxide) followed by synthesis of liquid products (such as diesel and naphtha) from the syngas using Fischer-Tropsch catalytic synthesis. The process is similar to that used in coal-to-liquids.

Geothermal: Geothermal energy is heat derived from the sub-surface of the earth. Water and/or steam carry the geothermal energy to the surface. Depending on its characteristics, geothermal energy can be used for heating and cooling purposes or be harnessed to generate clean electricity if the temperature is adequate.

Heat (end-use): Can be obtained from the combustion of fossil or renewable fuels, direct geothermal or solar heat systems, exothermic chemical processes and electricity (through resistance heating or heat pumps which can extract it from ambient air and liquids). This category refers to the wide range of end-uses, including space and water heating and cooking in buildings, desalination and process applications in industry. It does not include cooling applications.

Heat (supply): Obtained from the combustion of fuels, nuclear reactors, geothermal resources and the capture of sunlight. It may be used for heating or cooling, or converted into mechanical energy for transport or electricity generation. Commercial heat sold is reported under total final consumption with the fuel inputs allocated under power generation.

Hydrogen: In this report, hydrogen refers to low-carbon hydrogen unless otherwise stated. To be low-carbon hydrogen, either the emissions associated with fossil fuel-based hydrogen production must be prevented (e.g. by carbon capture, utilisation and storage) or the electricity for hydrogen production from water must be low-carbon electricity. Hydrogen is used in the energy system to refine hydrocarbon fuels and as an energy carrier in its own right. It is also produced from other energy products for use in chemicals production. In this report, total hydrogen demand includes gaseous hydrogen for all uses, including transformation into hydrogen-based fuels and biofuels, power generation, oil refining, and on site production and consumption. Final consumption of hydrogen includes gaseous hydrogen in end-use sectors, excluding transformation into hydrogen-based fuels and biofuels, power generation, oil refining and on site production and consumption.

Hydrogen-based fuels: Include ammonia and synthetic hydrocarbons (gases and liquids). Hydrogen-based is used in the figures in this *World Energy Outlook* to refer to hydrogen and hydrogen-based fuels.

Hydropower: 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.

Industry: The sector includes fuel used within the manufacturing and construction industries. Key industry branches include iron and steel, chemical and petrochemical, cement, aluminium, 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 other energy sector. There is an exception for fuel transformation in blast furnaces and coke ovens, which are reported within iron and steel. Consumption of fuels for the transport of goods is reported as part of the transport sector, while consumption by off-road vehicles is reported under industry.

International aviation bunkers: Includes the deliveries of aviation fuels to aircraft for international aviation. Fuels used by airlines for their road vehicles are excluded. The domestic/international split is determined on the basis of departure and landing locations and not by the nationality of the airline. For many countries this incorrectly excludes fuels used by domestically owned carriers for their international departures.

International marine bunkers: Covers those quantities delivered to ships of all flags that are engaged in international navigation. The international navigation may take place at sea, on inland lakes and waterways, and in coastal waters. Consumption by ships engaged in domestic navigation is excluded. The domestic/international split is determined on the basis of port of departure and port of arrival, and not by the flag or nationality of the ship. Consumption by fishing vessels and by military forces is excluded and instead included in the residential, services and agriculture category.

Investment: Investment is measured as the ongoing capital spending in energy supply capacity, energy infrastructure and energy end-use and efficiency. All investment data and projections reflect spending across the lifecycle of a project, i.e. the capital spent is assigned to the year when it is incurred. Fuel supply investments include production, transformation and transportation for oil, gas, coal and low emissions fuels. Power sector investments include new builds and refurbishments of generation, electricity grids (transmission, distribution and public electric vehicle chargers), and battery storage. Energy efficiency investments include those made in buildings, industry and transport. Other end-use investments include direct use of renewables; electric vehicles; electrification in buildings, industry and international marine transport; use of hydrogen and hydrogen-based fuels; fossil fuel-based industrial facilities; CCUS in industry and DACCUS. Investment data are presented in real terms in year-2020 US dollars unless otherwise stated.

Light-duty vehicles (LDVs): Includes passenger cars and light commercial vehicles (gross vehicle weight <3.5 tonnes).

Lignite: Type of coal that is used in the power sector mostly in regions near lignite mines due to its low energy content and typically high moisture levels, which generally makes long-distance transport uneconomic. Data on lignite in the *World Energy Outlook* includes peat, a solid formed from the partial decomposition of dead vegetation under conditions of high humidity and limited air access.

Liquid biofuels: Liquid fuels derived from biomass or waste feedstock and include ethanol, biodiesel and biojet fuels. They can be classified as conventional and advanced biofuels according to the combination of feedstock and technologies used to produce them and their respective maturity. Unless otherwise stated, biofuels are expressed in energy-equivalent volumes of gasoline, diesel and kerosene.

Liquid fuels: Includes oil, liquid biofuels (expressed in energy-equivalent volumes of gasoline and diesel), synthetic oil and ammonia.

Low-carbon electricity: Includes renewable energy technologies, hydrogen-based generation, nuclear power and fossil fuel power plants equipped with carbon capture, utilisation and storage.

Lower heating value: Heat liberated by the complete combustion of a unit of fuel when the water produced is assumed to remain as a vapour and the heat is not recovered.

Low emissions fuels: Include liquid biofuels, biogas and biomethane, hydrogen, and hydrogen-based fuels that do not emit any CO_2 from fossil fuels directly when used and also emit very little when being produced.

Marine: Represents the mechanical energy derived from tidal movement, wave motion or ocean currents and exploited for electricity generation.

Middle distillates: Include jet fuel, diesel and heating oil.

Mini-grids: Small electric grid systems, not connected to main electricity networks, linking a number of households and/or other consumers.

Modern energy access: Includes household access to a minimum level of electricity; household access to less harmful and more sustainable cooking and heating fuels, and stoves; access that enables productive economic activity; and access for public services.

Modern gaseous bioenergy: See biogases.

Modern liquid bioenergy: Includes bio-gasoline, biodiesel, biojet kerosene and other liquid biofuels.

Modern renewables: Include all uses of renewable energy with the exception of traditional use of solid biomass.

Modern solid bioenergy: Refers to the use of solid bioenergy in improved cook stoves and modern technologies using processed biomass such as pellets.

Natural gas: Comprises gases occurring in deposits, whether liquefied or gaseous, consisting mainly of methane. It includes both non-associated gas originating from fields producing hydrocarbons only in gaseous form, and associated gas produced in association with crude oil as well as methane recovered from coal mines (colliery gas). Natural gas liquids, manufactured gas (produced from municipal or industrial waste, or sewage) and quantities vented or flared are not included. Gas data in cubic metres are expressed on a gross calorific value basis and are measured at 15 °C and at 760 mm Hg (Standard Conditions). Gas data expressed in tonnes of oil equivalent, mainly for comparison reasons with other fuels, are on a net calorific basis. The difference between the net and the gross calorific value is the latent heat of vaporization of the water vapour produced during combustion of the fuel (for gas the net calorific value is 10% lower than the gross calorific value).

Natural gas liquids (NGLs): Liquid or liquefied hydrocarbons produced in the manufacture, purification and stabilisation of natural gas. NGLs are portions of natural gas recovered as liquids in separators, field facilities or gas processing plants. NGLs include, but are not limited to, ethane (when it is removed from the natural gas stream), propane, butane, pentane, natural gasoline and condensates.

Network gases: Include natural gas, biomethane, synthetic methane and hydrogen blended in a gas network.

Non-energy use: Fuels used for chemical feedstocks and non-energy products. Examples of non-energy products include lubricants, paraffin waxes, asphalt, bitumen, coal tars and oils as timber preservatives.

Nuclear: Refers to the primary energy equivalent of the electricity produced by a nuclear power plant, assuming an average conversion efficiency of 33%.

Off-grid systems: Stand-alone systems for individual households or groups of consumers.

Offshore wind: Refers to electricity produced by wind turbines that are installed in open water, usually in the ocean.

Oil: Includes both conventional and unconventional oil production. Petroleum products include refinery gas, ethane, liquid petroleum gas, aviation gasoline, motor gasoline, jet fuels, kerosene, gas/diesel oil, heavy fuel oil, naphtha, white spirits, lubricants, bitumen, paraffin, waxes and petroleum coke.

Other energy sector: 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. It also includes energy own use in coal mines, in oil and gas extraction and in electricity and heat production. Transfers and statistical differences are also included in this category. Fuel transformation in blast furnaces and coke ovens are not accounted in other energy sector.

Passenger cars: A road motor vehicle, other than a moped or a motorcycle, intended to transport passengers. It includes vans designed and used primarily to transport passengers. Excluded are light commercial vehicles, motor coaches, urban buses, and mini-buses/mini-coaches.

Power generation: Refers to fuel use in electricity plants, heat plants and combined heat and power plants. Both main activity producer plants and small plants that produce fuel for their own use (auto-producers) are included.

Process emissions: CO_2 emissions produced from industrial processes which chemically or physically transform materials. A notable example is cement production, in which CO_2 is emitted when calcium carbonate is transformed into lime, which in turn is used to produce clinker.

Productive uses: Energy used towards an economic purpose: agriculture, industry, services and non-energy use. Some energy demand from the transport sector (e.g. freight) could be considered as productive, but is treated separately.

Renewables: Includes bioenergy, geothermal, hydropower, solar photovoltaics (PV), concentrating solar power (CSP), wind and marine (tide and wave) energy for electricity and heat generation.

Residential: Energy used by households including space heating and cooling, water heating, lighting, appliances, electronic devices and cooking.

Road transport: Includes all road vehicle types (passenger cars, two/three-wheelers, light commercial vehicles, buses and medium and heavy freight trucks).

Self-sufficiency: Corresponds to indigenous production divided by total primary energy demand.

Services: Energy used in commercial facilities, e.g. offices, shops, hotels, restaurants, and in institutional buildings, e.g. schools, hospitals, public offices. Energy use in services includes space heating and cooling, water heating, lighting, appliances, cooking and desalination.

Shale gas: Natural gas contained within a commonly occurring rock classified as shale. Shale formations are characterised by low permeability, with more limited ability of gas to flow through the rock than is the case within a conventional reservoir. Shale gas is generally produced using hydraulic fracturing.

Shipping/navigation: This transport sub-sector includes both domestic and international navigation and their use of marine fuels. Domestic navigation covers the transport of goods or people on inland waterways and for national sea voyages (starts and ends in the same country without any intermediate foreign port). International navigation includes quantities of fuels delivered to merchant ships (including passenger ships) of any nationality for consumption during international voyages transporting goods or passengers.

Solar: Includes solar photovoltaics and concentrating solar power.

Solar photovoltaics (PV): Electricity produced from solar photovoltaic cells.

Solid bioenergy: Includes charcoal, fuelwood, dung, agricultural residues, wood waste and other solid wastes.

Solid fuels: Include coal, modern solid bioenergy, traditional use of biomass and industrial and municipal wastes.

Steam coal: Type of coal that is mainly used for heat production or steam-raising in power plants and, to a lesser extent, in industry. Typically, steam coal is not of sufficient quality for steel making. Coal of this quality is also commonly known as thermal coal.

Synthetic methane: Low-carbon synthetic methane is produced through the methanation of low-carbon hydrogen and carbon dioxide from a biogenic or atmospheric source.

Synthetic oil: Low-carbon synthetic oil produced through Fischer-Tropsch conversion or methanol synthesis from syngas, a mixture of hydrogen (H_2) and carbon monoxide (CO).

Tight oil: Oil produced from shale or other very low permeability formations, generally using hydraulic fracturing. This is also sometimes referred to as light tight oil. Tight oil includes tight crude oil and condensate production except for the United States, which includes tight crude oil only (US tight condensate volumes are included in natural gas liquids).

Total energy supply (TES): Represents domestic demand only and is broken down into electricity and heat generation, other energy sector and total final consumption.

Total final consumption (TFC): Is the sum of consumption by the various end-use sectors. TFC is broken down into energy demand in the following sectors: industry (including manufacturing, mining, chemicals production, blast furnaces and coke ovens), transport, buildings (including residential and services) and other (including agriculture and other non-energy use). It excludes international marine and aviation bunkers, except at world level where it is included in the transport sector.

Total final energy consumption (TFEC): Is a variable defined primarily for tracking progress towards target 7.2 of the United Nations Sustainable Development Goals. It incorporates total final consumption by end-use sectors but excludes non-energy use. It excludes international marine and aviation bunkers, except at world level. Typically this is used in the context of calculating the renewable energy share in total final energy consumption (indicator 7.2.1 of the Sustainable Development Goals), where TFEC is the denominator.

Total primary energy demand (TPED): See total energy supply.

Traditional use of biomass: Refers to the use of solid biomass with basic technologies, such as a three-stone fire, often with no or poorly operating chimneys.

Transport: Fuels and electricity used in the transport of goods or people within the national territory irrespective of the economic sector within which the activity occurs. This includes fuel and electricity delivered to vehicles using public roads or for use in rail vehicles; fuel delivered to vessels for domestic navigation; fuel delivered to aircraft for domestic aviation; and energy consumed in the delivery of fuels through pipelines. Fuel delivered to international marine and aviation bunkers is presented only at the world level and is excluded from the transport sector at a domestic level.

Trucks: Includes all size categories of commercial vehicles: light trucks (gross vehicle weight less than 3.5 tonnes); medium freight trucks (gross vehicle weight 3.5-15 tonnes); and heavy freight trucks (>15 tonnes).

Unabated coal: Consumption of coal in facilities without CCUS.

Unabated fossil fuels: Consumption of fossil fuels in facilities without CCUS.

Unabated gas: Consumption of natural gas in facilities without CCUS.

Useful energy: Refers to the energy that is available to end-users to satisfy their needs. This is also referred to as energy services demand. As result of transformation losses at the point of use, the amount of useful energy is lower than the corresponding final energy demand for most technologies. Equipment using electricity often has higher conversion efficiency than equipment using other fuels, meaning that for a unit of energy consumed, electricity can provide more energy services.

Variable renewable energy (VRE): Refers to technologies whose maximum output at any time depends on the availability of fluctuating renewable energy resources. VRE includes a broad array of technologies such as wind power, solar PV, run-of-river hydro, concentrating solar power (where no thermal storage is included) and marine (tidal and wave).

Zero carbon-ready buildings: A zero carbon-ready building is highly energy efficient and either uses renewable energy directly or an energy supply that can be fully decarbonised, such as electricity or district heat.

Zero emissions vehicles (ZEVs): Vehicles that are capable of operating without tailpipe CO_2 emissions (battery electric and fuel cell vehicles).

A1.2 Regional and country groupings

In several tables of this methodology document, as well as in the *WEO* publication itself, results from the *WEM* model are often presented with the below regional groupings.

Advanced economies: OECD regional grouping and Bulgaria, Croatia, Cyprus[1,2], Malta and Romania.

Africa: North Africa and sub-Saharan Africa regional groupings.

Asia Pacific: Southeast Asia regional grouping and Australia, Bangladesh, Democratic People's Republic of Korea (North Korea), India, Japan, Korea, Mongolia, Nepal, New Zealand, Pakistan, People's Republic of China (China), Sri Lanka, Chinese Taipei, and other Asia Pacific countries and territories.[3]

Caspian: Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan.

Central and South America: Argentina, Plurinational State of Bolivia (Bolivia), Brazil, Chile, Colombia, Costa Rica, Cuba, Curaçao, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, Uruguay, Bolivarian Republic of Venezuela (Venezuela), and other Central and South American countries and territories.[4]

China: Includes the (People's Republic of) China and Hong Kong, China.

Developing Asia: Asia Pacific regional grouping excluding Australia, Japan, Korea and New Zealand.

Emerging market and developing economies: All other countries not included in the advanced economies regional grouping.

Eurasia: Caspian regional grouping and the Russian Federation (Russia).

Europe: European Union regional grouping and Albania, Belarus, Bosnia and Herzegovina, North Macedonia, Gibraltar, Iceland, Israel[5], Kosovo, Montenegro, Norway, Serbia, Switzerland, Republic of Moldova, Turkey, Ukraine and United Kingdom.

European Union: Austria, Belgium, Bulgaria, Croatia, Cyprus[1,2], Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain and Sweden.

IEA (International Energy Agency): OECD regional grouping excluding Chile, Iceland, Israel, Latvia, Lithuania and Slovenia.

Latin America: Central and South America regional grouping and Mexico.

Middle East: Bahrain, Islamic Republic of Iran (Iran), Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic (Syria), United Arab Emirates and Yemen.

Non-OECD: All other countries not included in the OECD regional grouping.

Non-OPEC: All other countries not included in the OPEC regional grouping.

North Africa: Algeria, Egypt, Libya, Morocco and Tunisia.

North America: Canada, Mexico and United States.

OECD (Organisation for Economic Co-operation and Development): Australia, Austria, Belgium, Canada, Chile, Czech Republic, Colombia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom and United States. Costa Rica became a member of the OECD in May 2021; its membership is not yet reflected in the *World Energy Outlook* projections for the OECD grouping.

OPEC (Organisation of the Petroleum Exporting Countries): Algeria, Angola, Republic of the Congo (Congo), Equatorial Guinea, Gabon, the Islamic Republic of Iran (Iran), Iraq, Kuwait, Libya, Nigeria, Saudi Arabia, United Arab Emirates and Bolivarian Republic of Venezuela (Venezuela).

Southeast Asia: Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic (Lao PDR), Malaysia, Myanmar, Philippines, Singapore, Thailand and Viet Nam. These countries are all members of the Association of Southeast Asian Nations (ASEAN).

Sub-Saharan Africa: Angola, Benin, Botswana, Cameroon, Republic of the Congo (Congo), Côte d'Ivoire, Democratic Republic of the Congo, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Mauritius, Mozambique, Namibia, Niger, Nigeria, Senegal, South Africa, South Sudan, Sudan, United Republic of Tanzania (Tanzania), Togo, Zambia, Zimbabwe and other African countries and territories.[6]

Country notes

[1] Note by Turkey: The information in this document with reference to "Cyprus" relates to the southern part of the island. There is no single authority representing both Turkish and Greek Cypriot people on the island. Turkey recognises the Turkish

Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Turkey shall preserve its position concerning the "Cyprus issue".

[2] Note 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.

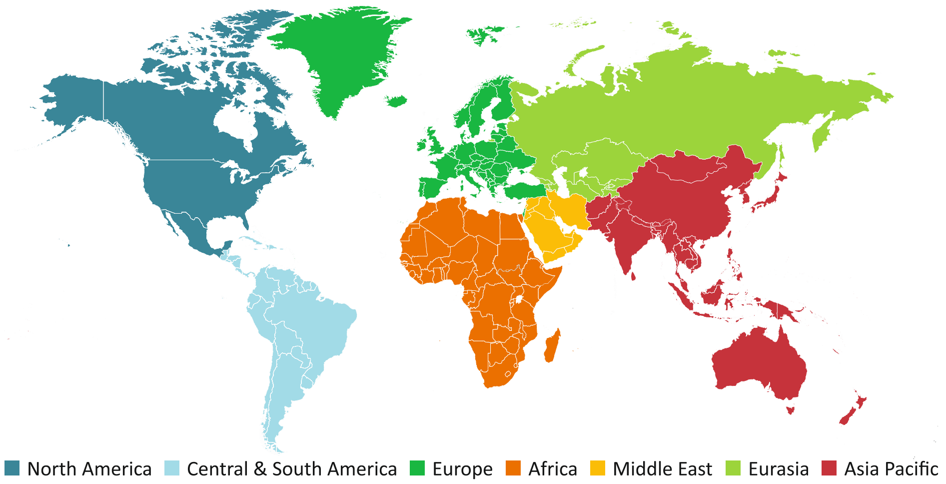
[3] Individual data are not available and are estimated in aggregate for: Afghanistan, Bhutan, Cook Islands, Fiji, French Polynesia, Kiribati, Macau (China), Maldives, New Caledonia, Palau, Papua New Guinea, Samoa, Solomon Islands, Timor-Leste and Tonga and Vanuatu.

[4] Individual data are not available and are estimated in aggregate for: Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bermuda, Bonaire, British Virgin Islands, Cayman Islands, Dominica, Falkland Islands (Malvinas), French Guiana, Grenada, Guadeloupe, Guyana, Martinique, Montserrat, Saba, Saint Eustatius, Saint Kitts and Nevis, Saint Lucia, Saint Pierre and Miquelon, Saint Vincent and Grenadines, Saint Maarten, Turks and Caicos Islands.

[5] 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.

[6] Individual data are not available and are estimated in aggregate for: Burkina Faso, Burundi, Cabo Verde, Central African Republic, Chad, Comoros, Djibouti, Kingdom of Eswatini, Gambia, Guinea, Guinea-Bissau, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Réunion, Rwanda, Sao Tome and Principe, Seychelles, Sierra Leone, Somalia and Uganda.

Figure 24: ***World Energy Outlook* regional groupings**



Note: This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

A1.3 Acronyms

APEC	Asia-Pacific Economic Cooperation
APS	Announced Pledges Scenario
ASEAN	Association of Southeast Asian Nations
BECCS	bioenergy equipped with CCUS
BEV	battery electric vehicles
CAAGR	compound average annual growth rate
CAFE	corporate average fuel economy standards (United States)
CBM	coalbed methane
CCGT	combined-cycle gas turbine
CCUS	carbon capture, utilisation and storage

CDR	carbon dioxide removal
CEM	Clean Energy Ministerial
CH4	methane
CHP	combined heat and power; the term co-generation is sometimes used
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CO_2-eq	carbon-dioxide equivalent
COP	Conference of Parties (UNFCCC)
CSP	concentrating solar power
CTG	coal-to-gas
CTL	coal-to-liquids
DAC	direct air capture
DACCUS	direct air capture with carbon capture, utilisation and storage
DER	distributed energy resources
DRI	direct reduced iron
DSI	demand-side integration
DSO	distribution system operator
DSR	demand-side response
EHOB	extra-heavy oil and bitumen
EOR	enhanced oil recovery
EPA	Environmental Protection Agency (United States)
ESG	environmental, social and governance
EU	European Union
EU ETS	European Union Emissions Trading System
EV	electric vehicle
FAO	Food and Agriculture Organization of the United Nations
FCEV	fuel cell electric vehicle
FDI	foreign direct investment
FiT	feed-in tariff
FOB	free on board
GDP	gross domestic product
GHG	greenhouse gases
GTL	gas-to-liquids
HEFA	hydrogenated esters and fatty acids
HFO	heavy fuel oil
IAEA	International Atomic Energy Agency
ICE	internal combustion engine
ICT	information and communication technologies
IEA	International Energy Agency
IGCC	integrated gasification combined-cycle
IIASA	International Institute for Applied Systems Analysis
IMF	International Monetary Fund
IMO	International Maritime Organization
IOC	international oil company
IPCC	Intergovernmental Panel on Climate Change
LCOE	levelised cost of electricity
LCV	light commercial vehicle
LDV	light-duty vehicle

LED	light-emitting diode
LNG	liquefied natural gas
LPG	liquefied petroleum gas
LULUCF	land use, land-use change and forestry
MEPS	minimum energy performance standards
MER	market exchange rate
NDCs	Nationally Determined Contributions
NEA	Nuclear Energy Agency (an agency within the OECD)
NGLs	natural gas liquids
NGV	natural gas vehicle
NOC	national oil company
NPV	net present value
NO_X	nitrogen oxides
N_2O	nitrous dioxide
NZE	Net Zero Emissions by 2050 Scenario
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
PHEV	plug-in hybrid electric vehicles
PLDV	passenger light-duty vehicle
PM	particulate matter
$PM_{2.5}$	fine particulate matter
PPA	power purchase agreement
PPP	purchasing power parity
PV	photovoltaics
R&D	research and development
RD&D	research, development and demonstration
SDG	Sustainable Development Goals (United Nations)
SDS	Sustainable Development Scenario
SME	small and medium enterprises
SMR	steam methane reformation
SO_2	sulphur dioxide
STEPS	Stated Policies Scenario
T&D	transmission and distribution
TES	thermal energy storage
TFC	total final consumption
TFEC	total final energy consumption
TPED	total primary energy demand
TSO	transmission system operator
UAE	United Arab Emirates
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
USGS	United States Geological Survey
VALCOE	value-adjusted levelised cost of electricity
VRE	variable renewable energy
WACC	weighted average cost of capital
WEM	World Energy Model

WEO	*World Energy Outlook*
WHO	World Health Organization
ZEV	zero emissions vehicle
ZCRB	zero carbon-ready building

A1.4 Oil and natural gas supply module

The *WEM* oil and natural gas supply module consists of 113 regions, of which 102 countries are modelled on an individual basis. Trade volumes broken downy by pipeline and liquefied natural gas are modelled for the following 20 regions: Canada, Mexico, United States, Brazil, Other Central and South America, European Union, Other OECD Europe, Other Non-OECD Europe, North Africa, West Africa, East Africa, Russia, Caspian, Middle East, OECD Asia, OECD Oceania, China, India, Southeast Asia, and Other Asia Pacific. The 102 countries modelled individually in the oil and natural gas module are categorised into the 20 natural gas trade regions in the following manner:

Canada: Canada.

Mexico: Mexico.

United States: United States.

Brazil: Brazil.

Other Central and South America: Argentina, Bolivia, Chile, Colombia, Cuba, Ecuador, Guyana, Paraguay, Peru, Trinidad and Tobago, Uruguay, and Venezuela.

European Union: Denmark, Estonia, France, Germany, Italy, Netherlands, Poland, Romania, Slovenia, and Sweden.

Other OECD Europe: Greenland, Israel, Norway, and the United Kingdom.

Other Non-OECD Europe: Ukraine.

North Africa: Algeria, Libya, Egypt, Tunisia, and Morocco.

West Africa: Angola, Benin, Cameroon, Central African Republic, Chad, Congo, Democratic Republic of Congo, Equatorial Guinea, Gabon, Gambia, Ghana, Guinea, Guinea Bissau, Ivory Coast, Liberia, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, and Togo.

East Africa: Botswana, Eritrea, Ethiopia, Kenya, Madagascar, Mozambique, Namibia, Seychelles, Somalia, South Africa, South Sudan, Sudan, Tanzania, and Uganda.

Russia: Russia.

Caspian: Azerbaijan, Kazakhstan, Turkmenistan, and Uzbekistan.

Middle East: Bahrain, Iran, Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, United Arab Emirates, and Yemen. Data for Saudi Arabia and Kuwait include 50% each of production from the Neutral Zone.

OECD Asia: Japan and Korea.

OECD Oceania: Australia and New Zealand.

China: China.

India: India.

Southeast Asia: Brunei Darussalam, Indonesia, Malaysia, Philippines, Thailand, and Viet Nam.

Other Asia Pacific: Bangladesh and Pakistan.

A1.5 Coal supply module

19 countries are modelled on an individual basis in the *WEM* coal supply module: Australia, Brazil, Canada, Chile, China, Colombia, India, Indonesia, Japan, Korea, Mexico, Mongolia, Mozambique, New Zealand, Russia, South Africa, the United States, Venezuela and Viet Nam.

Annex 2: References

Aboumahboub *et al.* (2010): Optimal Configuration of a Renewable-based Electricity Supply Sector, WSEAS Transactions on Power Systems (ISSN: 1790-5060), 2, p. 120-129, http://www.wseas.us/e-library/transactions/power/2010/89-612.pdf, accessed 28 June 2011

Airbus SAS (2004), *Global Market Forecast 2004-2023*, Airbus SAS, Blagnac, France.

AIM (Aviation Integrated Model), developed at UCL, https://www.ucl.ac.uk/energy-models/models/aim

Allen et al. (2016), *New use of global warming potentials to compare cumulative and short-lived climate pollutants*, Nature Climate Change (6).

Anandarajah, G. *et al.* (2011), *TIAM-UCL Global Model Documentation, UKERC Working Paper UKERC/WP/ESY/2011/001*, UK Energy Research Centre, London.

APP (Asia-Pacific Partnership on Clean Development and Climate) (2009), Energy Efficiency and Resource Saving Technologies in Cement Industry, APP, Washington D.C., http://www.asiapacificpartnership.org/english/cement_tf_docs.aspx

BGR (German Federal Institute for Geosciences and Natural Resources) (2014), *Energiestudie 2014, Reserven, Ressourcen und Verfügbarkeit von Energierohstoffen,* (Energy Study 2014, Reserves, Resources and Availability of Energy Resources), BGR, Hannover, Germany.

Bloomberg New Energy Finance (2020), *Energy Storage System Costs Survey 2020*

Boeing (2005), *Boeing Current Market Outlook 2005*, Boeing, Chicago.

Breiman, L. et al. (1984), *Classification and Regression Trees,* Wadsworth International, Belmont, United States.

CNI (Confederação nacional da indústria), IEL (Instituto Euvaldo Lodi), Eletrobras (2010a), *Oportunidades de eficiência energética para a indústria – setor cimenteiro [Opportunities for energy efficiency for industry – cement sector]*, CNI, Brasilia, Brazil

- (2010b), *Oportunidades de eficiência energética para a indústria – setor papel e celulose [Opportunities for energy efficiency for industry – pulp and papersector]*, CNI, Brasilia, Brazil

CSI (Cement Sustainability Initiative) (2013), *Existing and Potential Technologies for Carbon Emissions Reductions in the Indian Cement Industry*, CSI, Geneva.

CSI (Cement Sustainability Initiative) and ECRA (European Cement Research Academy) (2009), *Development of State of the Art-Techniques in Cement Manufacturing: Trying to Look Ahead*, CSI/ECRA Technology Paper, CSI, Geneva.

Cole, Wesley, A. Will Frazier, and Chad Augustine. (2021). *Cost Projections for Utility Scale Battery Storage: 2021 Update*. Golden, CO: National Renewable Energy

Laboratory. NREL/TP-6A20-79236. https://www.nrel.gov/docs/fy21osti/79236.pdf.

Dargay, J., D. Gately and M. Sommer (2006), "Vehicle Ownership and Income Growth, Worldwide: 1960-2030", *Energy Journal*, Vol. 28, No. 4, Elsevier, Amsterdam.

EC (European Commission) (2001), *Integrated Pollution Prevention and Control (IPPC) – Reference Document on Best Available Techniques in the Chlor-Alkali Manufacturing Industry*, EC, Brussels.

- (2003), *Integrated Pollution Prevention and Control (IPPC) – Reference Document on Best Available Techniques in the Large Volume Organic Chemical Industry*, EC, Brussels.

- (2010), *Integrated Pollution Prevention and Control (IPPC) – Reference Document on Best Available Techniques in the Pulp and Paper Industry*, EC, Brussels.

Econoler, *et al.* (2011), *Cooling Benchmarking Study Report*, Collaborative Labeling and Appliance Standards Program (CLASP), Brussels.

ENTSO-G (2017), Ten-Year Network Development Plan 2017, ENTSO-G, Brussels, Belgium.

- (2018), Ten-Year Network Development Plan 2018, ENTSO-G, Brussels, Belgium.

Eurofer (2014), *A steel roadmap for a low carbon Europe 2050*, The European Steel Association, Brussels.

EV Volumes (2020), https://www.ev-volumes.com/

EWITS (2011): *Eastern Wind Integration and Transmission Study, prepared for: The National Renewable Energy Laboratory*, prepared by: EnerNex Corporation, http://www.nrel.gov/wind/systemsintegration/pdfs/2010/ewits_final_report.pdf , accessed 28 June 2011. Data available on http://www.nrel.gov/wind/systemsintegration/ewits.html, accessed 28 June 2011

FAO (2019), Paper and paperboard production, Food and Agriculture Organization of the United Nations, Rome.

Fraunhofer ISI and FfE (2003*), Möglichkeiten, Potenziale, Hemmnisse und Instrumente zur Senkung des Energieverbrauchs branchenübergreifender Techniken in den Bereichen Industrie und Kleinverbrauch [Possibilities, potentials, barriers and instruments for the reduction of energy consumption from cross-cutting technologies in industry and small consumers]*, Fraunhofer Institute Systemtechnik und Innovationsforschung and Forschungsstelle für Energiewirtschaft e.V., Karlsruhe and München, Germany

Fraunhofer ISI et al (2009*), Study on the Energy Savings Potentials in EU Member States, Candidate Countries and EEA Countries*, Karlsruhe

Gately, D. (2006), "What Oil Export Levels Should We Expect from OPEC?", *Energy Journal*, Vol. 28, No. 2, Elsevier, Amsterdam.

GBPN (Global Buildings Performance Network) and CEU (Central European University) (2012), *Best Practice Policies for Low Carbon & Energy Buildings - Based on Scenario Analysis*, GBPN and CEU, Paris and Budapest.

Heide et al. (2010): Seasonal optimal mix of wind and solar power in a future, highly renewable Europe. Renewable Energy Vol. 35, p. 2483 - 2589, http://www.mng.org.uk/gh/resources/Heide_et_al2.pdf, accessed 28 June 2011

IATA (International Air Transport Association) (2012), Technology Roadmap Report 4th edition, IATA, Geneva, available at http://www.iata.org/whatwedo/environment/Documents/technology-roadmap-2013.pdf

ICAO (International Civil Aviation Organization) (2019), *Annual Report 2019, Air transport Statistics*, Montreal, available at https://www.icao.int/annual-report-019/Documents/ARC_2019_Air%20Transport%20Statistics.pdf

ICF (2016a), *Economic Analysis of Methane Emission Reduction Potential from Natural Gas Systems*. Fairfax, VA, United States: ICF.

– (2016b), *Summary of Methane Emission Reduction Opportunities Across North American Oil and Natural Gas Industries*. Fairfax, VA, United States: ICF.

IEA (International Energy Agency) (2007), *Tracking Industrial Energy Efficiency and* CO_2 *Emissions*, OECD/IEA, Paris.

– (2009), *Energy Technology Transitions for Industry*, OECD/IEA, Paris.

– (2010), *Energy Technology Perspectives 2010*, OECD/IEA, Paris.

– (2011), *Technology Roadmap: Energy-Efficient Buildings: Heating and Cooling Equipment*, OECD/IEA, Paris

– (2012a), *Energy Technology Perspectives 2012 – Pathways to a Clean Energy System*, OECD/IEA, Paris.

– (2012b), *Technology Roadmap: Fuel Economy of Road Vehicles,* OECD/IEA, Paris.

– (2013a), *Transition to Sustainable Building*, OECD/IEA, Paris

– (2013b), Technology Roadmap – Energy and GHG Reductions in the Chemical Industry via Catalytic Processes, OECD/IEA, Paris.

– (2013c), Technology Roadmap – Low-Carbon Technology for the Indian Cement Industry, OECD/IEA, Paris.

– (2014a), CO_2 Emissions from Fuel Combustion 2014, OECD/IEA, Paris.

– (2014b), *World Energy Investment Outlook: World Energy Outlook Special Report*, OECD/ IEA, Paris.

– (2015a), *WEO 2015 Special Report on Energy and Climate Change*, OECD/IEA, Paris.

– (2015b), *World Energy Outlook 2015*, OECD/IEA, Paris.

– (2016a), *WEO 2015 Special Report on Energy and Air Pollution*, OECD/IEA, Paris

– (2017a), *"Energy Sector Investment to Meet Climate Goals",* in *Perspectives for the Energy Transition – Investment Needs for a Low-Carbon Energy System,* 51–120, www.iea.org/publications/insights/insightpublications/PerspectivesfortheEnergyTransition.pdf

– (2017b), *Energy Access Outlook: from Poverty to Prosperity, World Energy Outlook Special Report*, OECD/IEA, Paris

– (2017c), *Energy Technology Perspectives - Catalysing Energy Technology Transformations*, OECD/IEA, Paris.

– (2017d), *World Energy Outlook 2017*, OECD/IEA, Paris.

– (2018a), *Global Electric Vehicle Outlook 2018*, OECD/IEA, Paris.

– (2018b), *World Energy Outlook 2018*, OECD/IEA, Paris.

– (2018c), *Technology Roadmap - Low-Carbon Transition in the Cement Industry*, OECD/IEA, Paris.

– (2019a), *Material efficiency in clean energy transitions*, IEA, Paris.

– (2019b), *World Energy Outlook 2019*, IEA, Paris.

– (2019c), *The Future of Hydrogen 2019*, IEA, Paris.

– (2019d), *World Energy Investment 2019*, IEA, Paris.

– (2020a), *Sustainable Recovery,* IEA, Paris.

– (2020b), *Energy Technology Perspectives 2020*, IEA, Paris.

- (2020c), World Energy Outlook 2020, OECD/IEA, Paris

IEA CCC (IEA Clean Coal Centre) (2012), *CO_2 abatement in the Iron and Steel Industry*, IEA CCC, London.

IIP and IFC (2014), *Waste Heat Recover for the Cement Sector: Market and Supplier Analysis*, Institute for industrial Productivity and International Finance Corporation, Washington D.C.

IMO (2014). Reduction of GHG emissions from ships - third IMO GHG study 2014. United Kingdom: London.

International Aluminium Institute (IAI) (2019), *Primary Aluminium Production*, London, http://www.world-aluminium.org/statistics/

IPCC (Intergovernmental Panel on Climate Change) (2021), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press.

IPCC (2018), *Global Warming of 1.5 °C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development and efforts to eradicate poverty*, [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.), World Meteorological Organization, Geneva, https://www.ipcc.ch/sr15/download/#full.

IPTS (Institute for Prospective Technological Studies) (2011), *Best Available Techniques (BAT) Reference Document for Iron and Steel Production*, European Commission, Seville, Spain.

Kannan, R. *et al.* (2007), *UK MARKAL Model Documentation*, UK Energy Research Centre, London, http://www.ukerc.ac.uk/support/tiki-index.php?page=ES_MARKAL_Documentation_2010.

Kaza, S. et al. (2018), What a Waste 2.0, A Global Snapshot of Solid Waste Management to 2050 , International Bank for Reconstruction and Development, The World Bank, Washington, DC

Ke, J. *et al.* (2012), “Potential Energy Savings and CO_2 Emissions Reduction of China’s Cement Industry”, *Energy Policy*, Vol. 45, Elsevier, Amsterdam, pp. 739-751.

Kermeli, K *et al.* (2015), “Energy efficiency improvement and GHG abatement in the global production of primary aluminium”, *Energy Efficiency*, Vol. 8 (4), Springer, Heidelberg, pp. 629-666.

Kesicki, F and A. Yanagisawa (2014), “Modelling the potential for industrial energy efficiency in IEA’s World Energy Outlook”, Energy Efficiency, Springer, Heidelberg

Koplow, D. (2009), *Measuring Energy Subsidies Using the Price-Gap Approach: What Does It Leave Out?*, International Institute for Sustainable Development, Winnipeg, Canada.

Kramer, K. *et al.* (2009), *Energy Efficiency Improvement and Cost Saving Opportunities for the Pulp and Paper Industry*, Lawrence Berkeley National Laboratory, Berkeley, United States.

Krause, J. *et al* (2017), *Light Duty Vehicle CO_2 Emission Reduction Cost Curves and Cost Assessment -the DIONE Model*, Publications Office of the European Union, Luxembourg.

Krause, J. and Donati, A (2018), *Heavy duty vehicle CO2 emission reduction cost curves and cost assessment – enhancement of the DIONE model CO_2*, Publications Office of the European Union, Luxembourg.

Lakner et al. (2021), *Updated estimates of the impact of COVID-19 on global poverty,* Global Poverty Monitoring Technical Note, World Bank, Washington, DC. https://blogs.worldbank.org/opendata/updated-estimates-impact-covid-19-global-poverty-turning-corner-pandemic-2021

LBNL (Lawrence Berkeley National Laboratory) (2012), *Bottom Up Energy Analysis System - Methodology and Results*, Lawrence Berkeley National Laboratory and The Collaborative Labeling and Appliance Standards Program.

Liu, G., Bangs, C.E. and D. B. Müller (2013), „Stock dynamics and emission pathways of the global aluminium cycle", *Nature Climate Change*, Vol. 3, Nature, London, pp. 338-342

Kong, L., *et al.* (2013), *Analysis of Energy-Efficiency Opportunities for the Pulp and Paper Industry in China*, Lawrence Berkeley National Laboratory and South China University of Technology, Berkeley, United States.

Korkovelos, A., et al. (2018), *A Geospatial Assessment of Small-Scale Hydropower Potential in Sub-Saharan Africa.* Energies, 11(11), 3100.

Madlool, N.A., *et al.* (2011), "A critical review on energy use and savings in the cement industries", *Renewable and Sustainable Energy Reviews*, Vol. 15, Elsevier, Amsterdam, pp. 2042-2060.

Martin, N., et al. (2000), *Opportunities to Improve Energy Efficiency and Reduce Greenhouse Gas Emissions in the U.S. Pulp and Paper Industry*, Lawrence Berkeley National Laboratory, Berkeley, United States.

Martinez, L., Kauppila, J., & Castaing Gachassin, M. (2014). International freight and related CO2 emissions by 2050: A new modelling tool Organisation for Economic Co-operation and Development. doi:10.1787/5jrw1kslrm9t-en

McNeil, M. and V. Letschert (2007), "Future Air Conditioning Energy Consumption in Developing Countries and What Can be Done about it: The Potential of Efficiency in the Residential Sector", *European Council for an Energy Efficient Economy (ECEEE) 2007 Summer Study*, ECEEE, pp. 1311-1322.

METI (2018), "Forecast of Global Supply and Demand Trends for Petrochemical Products (for the period 2009 to 2022)", Japan Ministry of Economy, Trade and Industry, Tokyo

Moya, J., N. Pardo and A. Mercier (2011), "The Potential for Improvements in Energy Efficiency and CO_2 Emissions in the EU27 Cement Industry and the Relationship with the Capital Budgeting Decision Criteria", *Journal of Cleaner Production*, Vol. 19, No. 11, Elsevier, Amsterdam, pp. 1207-1215.

NEA/IEA (Nuclear Energy Agency/International Energy Agency) (2010), *Projected Costs of Generating Electricity: 2010 Update*, OECD, Paris.

NEDO (New Energy and Industrial Technology Development Organisation) (2008), *Japanese Technologies for Energy Savings / GHG Emissions Reduction – 2008 Revised Edition*, NEDO, Kawasaki City, Japan.

Neelis, M., E. Worrell and E. Masanet (2008), *Energy Efficiency Improvement and Cost Saving Opportunities for the Petrochemical Industry*, Lawrence Berkeley National Laboratory, Berkeley, United States.

Neelis, M., *et al.* (2012), Climate protection with rapid payback – Energy and CO_2 savings potential of industrial insulation in EU27, Ecofys and European Industrial Insulation Foundation, Utrecht, The Netherlands and Gland, Switzerland.

NRC (National Research Council) (2010), *Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles*, The National Academy Press, Washington, DC.

NREL (2010): National Solar Radiation Data Base, 1991-2005 Update, http://rredc.nrel.gov/solar/old_data/nsrdb/, accessed 28 June 2011

OAG (Official aviation Guide) (2020), https://www.oag.com/

Oda, J, *et al.* (2012), "International Comparisons of Energy Efficiency in Power, Steel and Cement Industries", *Energy Policy*, Vol. 44, Elsevier, Amsterdam, pp. 118-129.

OGJ (Oil and Gas Journal) (2014), "Global Reserves, Oil Production Show Increases for 2014", *OGJ*, Pennwell Corporation, Oklahoma City, United States.

OECD (Organisation for Economic Co-operation and Development) (2012a), *The OECD ENV-Linkages Modelling Framework*, OECD, Paris.

− (2012b), *OECD Environmental Outlook to 2050*, OECD, Paris.

OECD/FAO (2018), *OECD-FAO Agricultural Outlook 2018-2027,* OECD Publishing, Paris/Food and Agriculture Organization of the United Nations, Rome

Okazaki, T. and M. Yamaguchi (2011), "Accelerating the Transfer and Diffusion of Energy Saving Technologies Steel Sector Experience – Lessons Learned", *Energy Policy*, Vol. 39, Elsevier, Amsterdam, pp. 1296-1304.

Pardo, N., J.A. Moya and K. Vatopoulos (2012), *Prospective Scenarios on Energy Efficiency and CO_2 Emissions in the EU Iron & Steel Industry*, European Commission Joint Research Centre, Petten, Netherlands

Ren, T., M.K. Patel and K. Blok (2008), " Steam cracking and methane to olefins: Energy use, CO_2 emissions and production costs ", Energy, Vol. 33, Elsevier, Amsterdam, pp. 817-833.

RISI (Resource Information System Inc) (2019), Pulp and paper industry database, RISI, Boston.

Sander+Partner GmbH (2010) http://www.sander-partner.ch/en/index.html, accessed 28 June 2011

Saygin, D., *et al.* (2009), *Chemical and petrochemical sector – Potential of best practice technology and other measures for improving energy efficiency*, OECED/IEA, Paris.

Saygin, D., *et al.* (2011), "Potential of best practice technology to improve energy efficiency in the global chemical and petrochemical sector", *Energy*, Vol. 36, Elsevier, Amsterdam, pp. 5779-5790.

Schmidt, O., Hawkes, A., Gambhir, A. et al (2017). *The future cost of electrical energy storage based on experience rates*. Nat Energy 2, 17110 (2017). https://doi.org/10.1038/nenergy.2017.110

Schipper L., C. Marie-Liliu, and R. Gorham (2000), *Flexing the link between Transpor and Greenhouse Gas Emissions: a path for the World Bank*, International Energy Agency/OECD, Paris.

Suranjana *et al. (2010):* The NCEP Climate Forecast System Reanalysis. Bull. Amer. Soc. Vol 91, p. 1015 – 1057

Tsiropoulos, I., Tarvydas, D. and Lebedeva (2018) N., *Li-ion batteries for mobility and stationary storage applications*, Publications Office of the European Union.
https://publications.jrc.ec.europa.eu/repository/handle/JRC113360

Tsinghua University (2008), *Assisting Developing Country Climate Negotiators through Analysis and Dialogue: Report of Energy Saving and CO_2 Emission Reduction Analysis in China Cement Industry*, Tsinghua University, Beijing.

Ueckerdt, F., *et. al*. (2016). Decarbonizing global power supply under region-specific consideration of challenges and options of integrating variable renewables in the REMIND model. *Energy Economics*.

UNIDO (United Nations Industrial Development Organization) (2010), *Global Industrial Energy Efficiency Benchmarking – An Energy Policy Tool*, UNIDO, Vienna.

− (2011), *Industrial Development Report 2011 – Industrial Energy Efficiency for Sustainable Wealth Creation*, UNIDO, Vienna.

UNPD (United Nations Population Division) (2019), *World Population Prospects: The 2019 Revision*, UNPD, New York.

UNWTO (2012). UNWTO Tourism Highlights 2012. United Nations World Tourism Organization. Available at: http://mkt.unwto.org/en/publication/unwto-tourism-highlights-2013-edition.

US DOE/EIA/ARI (Department of Energy/Energy Information Administration)/(Advanced Resources International) (2013), *Technically Recoverable Shale Oil and Shale Gas Resources: An Assessment of 137 Shale Formations in 41 Countries Outside the United States*, US DOE/EIA, Washington, DC.

US EPA (United States Environmental Protection Agency) (2010a), *Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Iron and Steel Industry*, US EPA, Washington, DC.

− (2010b), *Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Portland Cement Industry*, US EPA, Washington D.C.

− (2010c), *Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Pulp and Paper Manufacturing Industry*, US EPA, Washington, DC.

− (2013), *Draft Inventory of US Greenhouse Gas Emissions and Sinks: 1990-2011*, US EPA, Washington, DC.

USGS (United States Geological Survey) (2012a), "Assessment of Potential Additions to Conventional Oil and Gas Resources of the World (Outside the United States) from Reserves Growth*", Fact Sheet FS2012-3052*, USGS, Boulder, United States.

− (2012b), "An Estimate of Undiscovered Conventional Oil and Gas Resources of the World"*, Fact Sheet 2012-3042*, USGS, Boulder, United States.

− (2018a), *Nitrogen (Fixed) – Ammonia*, Boulder, United States.

− (2018b), *Cement*, USGS, Boulder, United States.

Waide, P. (2011), *Opportunities for Success and CO_2 Savings from Appliance Energy Efficiency Harmonization*, Navigant Consulting and CLASP, London and Brussels.

Wen, Z. and H. Li (2014), "Analysis of potential energy conservation and CO2 emissions reduction in China's non-ferrous metals industry from a technology perspective", *International Journal of Greenhouse Gas Control*, Vol. 28, Elsevier, Amsterdam, pp. 45-56.

WEPROG (2010), Weather and wind Energy Prognosis http://www.weprog.com/information, accessed 28 June 2011

WHO (2021), Cooking fuel and technology database https://www.who.int/data/gho/data/themes/air-pollution/cooking-fuel-and-technology-database-by-fuel-category

World Steel Association (2019), *Steel Production 2018,* World Steel Association, Brussels.

WWITS (2010), Western Wind and Solar Integration Study, prepared for: The National Renewable Energy Laboratory, prepared by: GE Energy, http://www.nrel.gov/wind/systemsintegration/pdfs/2010/wwsis_final_report.pdf , accessed 28 June 2011. Data available on http://www.nrel.gov/wind/systemsintegration/wwsis.html, accessed 28 June 2011

Zhou, W., et al. (2010), "CO_2 emissions and mitigation potential in China's ammonia industry", *Energy Policy*, Vol. 38, Elsevier, Amsterdam, pp. 3701-3709.