# Global Energy and Climate Model

## Documentation - 2026



International Energy Agency

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# Overview of model and scenarios

Since 1993, the IEA has provided medium- to long-term energy projections using a continually evolving set of detailed, world-leading modelling tools. First, the World Energy Model (WEM) – a large-scale simulation model designed to replicate how energy markets function – was developed. A decade later, the Energy Technology Perspectives (ETP) model – a technology-rich bottom-up model – was developed for use in parallel to the WEM.

Over the past five years, the IEA has worked to develop a new integrated modelling framework: the IEA's Global Energy and Climate (GEC) Model. This model is now the principal tool used to generate detailed sector-by-sector and region-by-region long-term scenarios across the IEA's publications.

The GEC Model brings together the modelling capabilities of the WEM and ETP models. The result is a large-scale, bottom-up simulation modelling framework with elements of optimisation, allowing for a unique set of analytical capacities in energy markets, technology trends, policy strategies and investments across the energy sector. The IEA's GEC Model covers 29 regions that can be aggregated to world-level results, and it covers all sectors across the energy system with dedicated bottom-up modelling for:

- **Final energy demand**, covering industry, transport, buildings, agriculture and non-energy use. This is driven by detailed modelling of energy service and material demand.
- **Energy transformation**, including electricity generation and heat production, refineries, the production of biofuels, hydrogen and hydrogen-based fuels, and other energy-related processes, as well as related transmission and distribution systems, storage and trade.
- **Energy supply**, including fossil fuel exploration, extraction and trade, and the availability of renewable energy resources.

The GEC Model is a highly 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 (IEA, 2026a). The model also draws on data from collaboration with other institutions and from a wide range of external sources, which are indicated in the relevant sections of this document. The development of the GEC Model benefited from expert review within the IEA and beyond, and the IEA continues to work closely with colleagues in the international modelling community.

The GEC Model is designed to analyse a diverse range of aspects of the energy system, including:

- **Global and regional energy prospects:** Including 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:** Including carbon dioxide ($CO_2$) emissions from fuel combustion, industrial processes and flaring; methane ($CH_4$) emissions from fossil fuel operations; $CH_4$ and nitrous oxide ($N_2O$) emissions from final energy demand and energy transformation; local air pollutants; and temperature outcomes.
- **Effects of policy actions and technological changes:** Including the impact of a range of policy actions and technological developments on energy demand, supply, trade, investments and emissions.
- **Investment in the energy sector:** Including investment requirements in fuel and technology supply chains to satisfy projected energy demand, and demand-side investment requirements.
- **Modern energy access assessments:** Including trends in access to electricity and clean cooking, as well as the related additional energy demand and investments, and changes in greenhouse gas (GHG) emissions.
- **Energy employment:** Including the impact of the energy sector's evolution on employment in each scenario.

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## 1.1 GEC Model scenarios

The IEA's medium- to long-term outlook publications – including the *World Energy Outlook* (WEO) and *Energy Technology Perspectives* (ETP) – use a scenario approach relying on the GEC Model to examine future energy trends. The GEC Model is used to explore multiple scenarios, each of which is built on a different set of underlying assumptions about how the energy system might evolve over time. By comparing them, readers can assess what drives the various outcomes, and the opportunities and pitfalls that lie along the way. These scenarios are not forecasts and do not contain a single view about what the long-term future might hold. Instead, the scenarios seek to enable readers to compare different possible versions of the future, and the levers and actions that produce them, and to gain insights into the future of global energy.

The 2026 Middle East conflict has been a major shock to the energy system. A key objective of this year's *Outlook* is to examine how this shock might affect government policy preferences, particularly among energy-importing countries, together with what this might mean for energy security, affordability and emissions. There is still a high degree of uncertainty over how and when the conflict in the Middle East might be resolved and how stable any resolution might be. In our scenarios, constraints on exports from the Gulf arising from the conflict are assumed to ease as we move into 2027, and conditions are assumed to be sufficiently stable to allow for unimpeded transit through the Strait by the end of 2027. This does not, however, return the energy world to the situation that existed prior to the conflict, as our exploratory scenarios reflect to different degrees the impact of lasting changes in policies and risk perceptions.

The World Energy Outlook, Energy Technology Perspectives and their related reports explore different aspects through a spectrum of scenarios, all of which are fully updated to include the latest energy market and cost data. The Current Policies Scenario (CPS) and the Stated Policies Scenario (STEPS) are exploratory, in that they define a set of starting conditions, such as policies and targets, and see where these conditions lead based on model representations of energy systems that reflect market dynamics and technological progress.

In addition, we include here details on three scenarios that have normative elements relating to energy access or the achievement of various goals related to emissions. This means that these scenarios work toward a defined outcome and map out a way to achieve it. The Net Zero Emissions by 2050 Scenario shows a global pathway to reach net zero emissions from the energy sector by 2050 without offsets from other sectors, an emissions trajectory consistent with keeping the temperature rise in 2100 below 1.5 °C (with at least a 50% probability). The Accelerating Clean Cooking and Electricity Services Scenario (ACCESS) represents a roadmap to achieve universal access to electricity by 2035 and clean cooking by 2040. The Announced Pledges Scenario (APS) assumes that all national energy and climate targets are achieved in full and on time. The *World Energy Outlook 2026* (*WEO-2026*) does not include an update to the ACCESS or APS.

The scenarios highlight the importance of government policies in determining the future of the global energy system: decisions made by governments are a critical differentiating factor explaining the variations in outcomes across our scenarios. However, we also take into account other elements and influences, notably the economic and demographic context, technology costs and learning, energy prices and affordability, corporate sustainability commitments, and social and behavioural factors. While the evolving costs of known technologies are modelled in detail, we do not try to anticipate technology breakthroughs (e.g. nuclear fusion).

An inventory of the key policy assumptions, along with the underlying data on population, economic growth, resources, technology costs and fossil fuel prices, is available in Section 2.

The *WEO-2026* also includes two new cases – the Additional Response Case (ARC) and the Low Hormuz Case (LHC) – that expand our analysis of the potential implications of the 2026 conflict in the Middle East beyond those captured in the exploratory scenarios.

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### 1.1.1 Current Policies Scenario

The CPS is an exploratory scenario in which no change in energy-related policies is assumed beyond what is firmly in place – for *WEO-2026*, as at August 2026 – and no further action is assumed on time-limited policies once they expire. Given the time it takes to formally adopt new legislation and regulation, this scenario does not incorporate policy responses to the Middle East conflict. It does, however, capture some near-term responses and behavioural changes that could have longer-term implications, such as the observed change in consumer purchasing behaviour for electric vehicles (EVs) and rooftop solar, and the easing of operational restrictions on coal-fired power in some countries. The CPS offers a generally cautious perspective on the speed at which new energy technologies are deployed and integrated into the energy system, and it tends to project slower growth in the adoption of new technologies than has been seen in recent years or is projected in the Stated Policies Scenario.

### 1.1.2 Stated Policies Scenario

The STEPS builds on a broader reading of the policy landscape than the CPS. Alongside policies already in place, it takes account of concrete policy proposals and official strategy documents that indicate the direction in which governments intend to move. For *WEO-2026, this includes* measures developed in response to the Middle East conflict as of August 2026, such as new plans and targets to expand renewable and clean electricity generation (as in Indonesia, Korea and Thailand); new initiatives to support transport electrification (as in the European Union and Indonesia); additional support for energy efficiency improvements (as in Canada, China and Türkiye); and measures to increase the use of biofuels (as in Brazil). In addition, the STEPS offers a more dynamic perspective on energy technology and market trends than the CPS, allowing for a more rapid introduction of new energy technologies.

### 1.1.3 Accelerating Clean Cooking and Electricity Services Scenario (ACCESS)

Rapid progress on energy access has been made in recent decades in some regions and countries. Still, billions of people in around 100 countries remain without access to basic modern energy services, and the number of people without access to energy in sub-Saharan Africa has risen since 2010. Included in *World Energy Outlook 2025* (*WEO-2025*), the ACCESS presents a data-driven roadmap to achieve universal access to electricity by 2035 and clean cooking by 2040. It is grounded in practical constraints and solutions, examining what historical rates of progress have been achieved, and then it prioritises cost-effective, proven means to replicate those successes in comparable contexts. It explores all relevant fuels and technologies needed to achieve universal access, as well as the infrastructure, policies and financing needed to scale them up. The ACCESS applies the same prevailing technology cost and fuel price assumptions as the STEPS.

### 1.1.4 Net Zero Emissions by 2050 Scenario

The Net Zero Emissions by 2050 (NZE) Scenario is specifically designed to achieve an ambitious reduction in energy-related emissions. It maps out a way for the global energy system to achieve net zero $CO_2$ emissions by 2050 and is consistent with a long-term goal of limiting the rise in global average temperatures to 1.5 °C (with at least a 50% probability). In the light of persistently high emissions in recent years, warming in this scenario peaks just below 1.7 °C and exceeds 1.5 °C for several decades before returning below 1.5 °C by 2100. This requires a very rapid transformation of the energy sector, along with the widespread deployment of $CO_2$ removal technologies.

### 1.1.5 Announced Pledges Scenario

The APS was introduced in 2021 and updated in *World Energy Outlook 2024* (*WEO-2024*). The APS aims to illustrate the extent to which announced ambitions and targets can deliver the emissions reductions needed to

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achieve net zero emissions by 2050. It includes all recent major national announcements for 2030 and 2035 targets as well as longer-term net zero or carbon neutrality pledges, regardless of whether these announcements have been anchored in legislation or in updated nationally determined contributions (NDCs). In the APS, countries fully implement their national targets, and the outlook for exporters of fossil fuels and low-emissions fuels such as hydrogen is shaped by what full implementation of all targets means for global demand. The APS also assumes that all country targets for access to electricity and clean cooking are achieved on time and in full.

The way these pledges are assumed to be implemented in the APS has important implications for the energy system. A net zero pledge for economy-wide GHG emissions does not necessarily mean that $CO_2$ emissions from the energy sector need to reach net zero. For example, a country's net zero plans may envisage that some remaining energy-related emissions are offset by the absorption of emissions from forestry or land use. It is not possible to know exactly how net zero pledges will be implemented, but the design of the APS, particularly regarding the details of the energy system pathway, has been informed by the pathways that a number of national bodies have developed to support net zero pledges. For countries that have not yet made a net zero pledge, policies are assumed to be the same as in the STEPS. Non-policy assumptions, including population and economic growth, are the same as in the STEPS.

### *1.1.6 Additional Response Case*

The ARC was introduced in *WEO-2026*. It goes further than the CPS and the STEPS in accounting for possible responses to the disruptions in energy markets in 2026. Most countries have been focused on managing the immediate impacts of the 2026 conflict in the Middle East and have not yet had time to formulate longer-term policy responses that would qualify for inclusion in the CPS or the STEPS. Nonetheless, there are preliminary indications in speeches and other public statements of how governments' longer-term policy priorities could evolve in response to the crisis. The ARC explores what would happen if these potential changes were turned into actionable policy proposals and then implemented. It therefore goes beyond the measures captured in the STEPS to examine how a more far-reaching response to heightened energy security concerns could reshape the energy system over time. This brings into play a range of additional demand- and supply-side measures, which typically put greater emphasis on efforts to diversify fuel suppliers and import routes; strengthened incentives or frameworks to develop domestically available resources and improve energy efficiency; and a stronger push for electrification of end-use consumption, for instance for transport. Insofar as these measures affect demand for imported oil and natural gas, the response from most exporters is to use more of their production at home, so their domestic energy mix tends more towards what is seen in the CPS. However, this varies by country.

### *1.1.7 Low Hormuz Case*

The LHC was introduced in *WEO-2026*. While the ARC looks at a range of possible additional responses to heightened energy security concerns, the LHC addresses a specific issue: whether and how the energy world could manage without the transit of energy supplies through the Strait of Hormuz.

## 1.2 Selected developments in 2026

The primary sectoral and topic-specific model developments undertaken this year include the following:

### *Cross-cutting*

#### Investment

- Investment in public electric vehicle charging has been updated to count towards spending in the end-use sector rather than the power sector. Public electric vehicle charging investment is based on estimates of utility-led charger installations with prevailing cost information.

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### Useful energy demand

- The useful energy demand model was updated and aligned across end-use sectors to fully consider the sub-sectoral and technology wealth of the industry, transport and buildings models. The useful energy demand model was adjusted to match different modelling methodology choices, for instance across industry sub-sectors (energy-intensive industries that are modelled bottom-up, other energy-intensive industries and non-energy-intensive industries). Data linking activity, useful demand and final demand were updated, including equipment efficiency and theoretical energy inputs for material production.

## *Final energy consumption*

### Industry

- The end-use module for industry splitting energy demand between heat, mechanical, cooling, lighting and other has been improved, leveraging the Manufacturing Energy Consumption Survey update (EIA, 2025) and additional publicly available data. This enhancement improved the assessment of thermal energy storage requirements.
- The endogenous learning rates for the industrial materials modelled at the technology level have been improved. CAPEX and fixed OPEX decrease as cumulative capacity increases, with each doubling triggering a further cost reduction. Learning rates are differentiated by technology maturity, with lower rates for mature technologies and higher rates for emerging technologies.

### Transport

- The rail activity module now applies a common approach to all rail modes, projecting passenger and freight activity using elasticities to gross domestic product (GDP), population and track length. The elasticities are estimated for eight clusters, from country-level historical data. Each cluster groups several GEC Model regions, giving every estimate enough data while capturing different levels of rail network maturity. Future track length is derived from project-level data and infrastructure pathways differ by scenario according to each project's stage of development.
- The road transport model has been enhanced with a dedicated used-car trade module. The used-car module projects bilateral flows of used passenger cars across GEC Model regions, balancing import demand and export supply based on historical trade patterns, economic developments, car purchase cost and price depreciation, as well as average imported vehicle age and retirements. It accounts for policy constraints such as vehicle age restrictions and bans on used internal combustion engine (ICE) vehicle imports. By capturing changes in the powertrain composition of exporting fleets, including increasing electrification, the module assesses how international used-car trade influences the technological composition and fuel economy of car fleets in regions.
- A dedicated Electric Vehicle Supply Equipment (EVSE) module has been developed to project the stock of charging infrastructure by vehicle category, accounting for historical deployment trends, charging technology mix, access to private charging and the evolution of EV adoption. For light-duty vehicles, public charging requirements are calibrated using historical EVSE-to-EV ratios and the shares of slow and fast chargers, with the charging mix gradually shifting towards higher-power technologies. For buses and trucks, public charging needs are estimated based on the projected share of electricity demand met through opportunity and public charging, as well as the assumed mix of charging capacities. The module also captures declining infrastructure costs through learning curves and estimates the associated investment requirements, including both new installations and the replacement of retired equipment.

### Buildings

- A new set of projections for heating and cooling degree days was developed in collaboration with Climate Resource, which conducted climate modelling based on emissions pathways in IEA scenarios.

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- The methodology for estimating historical equipment sales was revised to reinforce the coherence with relevant markets and energy balances.
- The appliance efficiency modelling was revised, building on historical efficiency standards and labels collected across major markets.
- The ownership model for appliances and cooling was enhanced by expanding the historical ownership database and linking the saturation of air conditioner penetration with the regional distribution of cooling needs.
- The envelope module was upgraded for the services sector (continuing developments on the residential sector last year) with new data across several dimensions, notably on the energy performance of different building types and their share in new buildings, based on the scope, stringency and enforcement of building codes.

#### Energy access

- A new statistical approach has been developed using night-time light satellite imagery to track recent progress on electrification by country. Satellite observations are processed, combined with population data and calibrated against household surveys to identify changes associated with electricity access. These estimates complement traditional survey and supply-side data, providing more timely insights into electrification trends.
- A new econometric approach has been developed to provide more timely estimates of recent progress in clean cooking access for years for which household survey data are not yet available.
- Econometric models projecting long-term electricity and clean cooking access rates have been updated to better account for new energy access programmes and investment commitments.
- Estimates of energy demand associated with electricity and clean cooking access have been refined to incorporate the latest evidence from academic research.

### *Electricity generation*

- The treatment of variable renewable energy curtailment has been enhanced, with curtailment now explicitly allocated between wind and solar PV and reported separately. Wind and solar PV generation is consequently reported as realised generation, excluding curtailed output, rather than as available generation before curtailment.
- In the electricity grids module, an improved representation of the relationship between increased electricity demand, GDP per capita and electricity grids growth has been developed. This consists of region-specific detail, with multiple equations for distribution as well as for transmission.

### *Energy supply*

- Data have been collected on existing intra-regional gas transmission and distribution networks. A geospatial model to project evolution of gas grids by scenario has also been designed. From existing statistics, such as total length per pressure level, number of connections, population and building densities as well as injection points, a set of synthetic networks is created for the base year. Then changes in regional gas supply and demand are absorbed into the synthetic network in three possible ways: modulation of household and industrial gas demand (no impact on pipelines), increases or decreases in local connection density, and the connection or disconnection of entire neighbourhoods.

### *Employment*

- Model coverage has been broadened to include critical minerals refining and two/three-wheeler manufacturing.

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## 1.3 GEC Model overview

### *1.3.1 Modelling methodology*

The GEC Model is a large-scale, bottom-up simulation modelling framework with elements of optimisation, covering energy demand, energy transformation and energy supply. The model uses a partial equilibrium approach, integrating price sensitivities. It shows the transformation of primary energy along energy supply chains to meet energy service demand, and the final energy demand needed to serve it. The supply, transformation and demand modules of the model are dynamically soft-linked: consumption of electricity, hydrogen and hydrogen-related fuels, biofuels, oil products, coal and natural gas in the end-use sector model drives the transformation and supply modules, which in turn feed energy prices back to the demand module in an iterative process. In addition, energy system $CO_2$, methane ($CH_4$) and nitrous oxide ($N_2O$) emissions are assessed. The model also comprises additional modules evaluating system implications such as investments, critical minerals, employment, temperature outcomes, land use and air pollution.

The main exogenous drivers of the scenarios are economic growth, demographic change and technological developments. Energy service demand drivers, such as steel demand in industry or the number of appliances owned by each household, are estimated econometrically based on historical data and on the socioeconomic drivers. Interactions between energy service demand drivers, such as the influence of the number of vehicle sales on materials demand, are also accounted for.

This service demand is met by existing and new technologies. All sector modules (see subsequent sections for more details) base their projections on the existing stock of energy infrastructure (e.g. the production capacity in industry, floorspace in buildings, number of vehicles in transport), through detailed stock-accounting frameworks. To assess how service demand is met in the various scenarios, the model includes a wide range of fuels and technologies (existing and new). This includes careful accounting of the current energy performance of different technologies and processes, and the potential for energy efficiency improvements.

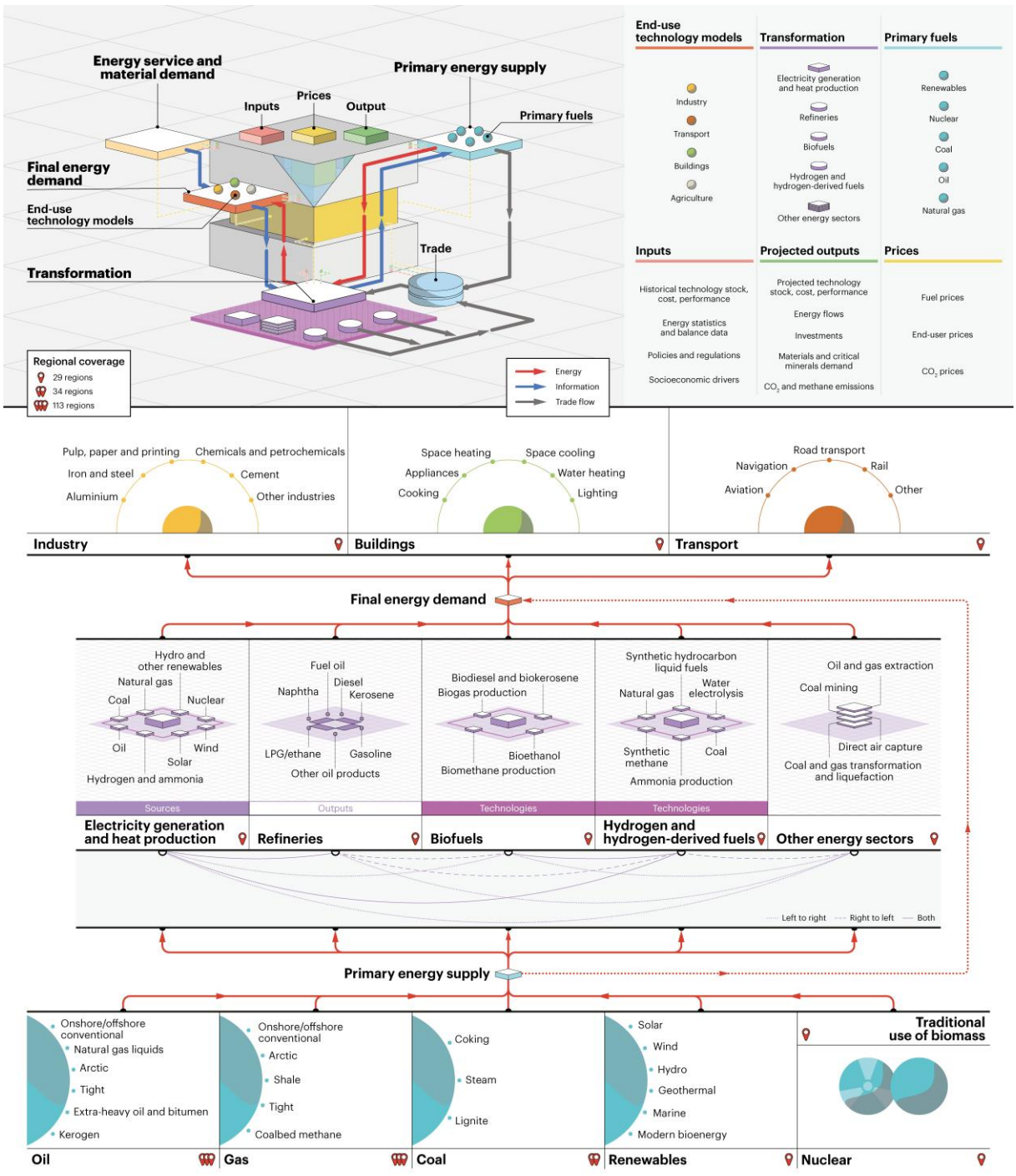
The sectoral energy and emission balances are calculated based on the final energy end uses – the service demand – by determining first the final energy demand needed to serve it, then the transformations to convert primary energy into the required fuels, and finally the primary energy needs. This is based on a partial equilibrium approach using, for some elements, a partial-optimisation model, within which specific costs play an important role in determining the share of fuels and technologies to satisfy 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. These include investment costs, operating and maintenance costs, fuel costs and, in some cases, costs for emitting $CO_2$. In certain sectors, such as hydrogen production, specially designed and linked optimisation modules are used.

While the model aims to identify an economical way for society to reach the desired scenario outcomes, the results do not necessarily reflect the least-cost pathway. This is because an unconstrained least-cost approach may fail to take account of all the issues that need to be considered in practice, such as market failures, political or individual preferences, feasible ramp-up rates, capital constraints and public acceptance. Instead, the analysis pursues a portfolio of fuels and technologies within a framework of cost minimisation, considering technical, economic and regulatory constraints. This approach, tailored to each sector and incorporating extensive expert consultation, enables the model to reflect as accurately as possible the realities of different sectors. It also offers a hedge against the real risks associated with the pathways: if one technology or fuel fails to fulfil its expected potential, it can more easily be compensated for by another if its share in the overall energy mix is low.

All fuels and technologies included in the model are either already commercially available or at a relatively advanced stage of development, and they therefore have at least reached a prototype size from which enough information about expected performance and costs at scale can be derived. Costs for new clean fuels and technologies are informed in many cases by learning curve approaches and are expected to fall over time, helping to make a net zero future economically feasible.

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**Figure 1.1 ▷ Global Energy and Climate Model overview**




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Besides this main feedback loop between supply and demand, there are also linkages between the transformation and supply modules, and further linkages such as material flows or biogenic or atmospheric $CO_2$ via direct air capture (DAC) for synthetic fuel production. Primary energy needs and availability interact with the supply module. 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, taking into account reductions from $CO_2$ removal technologies.

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The GEC Model is implemented in the simulation software Vensim (Ventana Systems Inc., 2026), but it makes use of a wider range of software tools, including TIMES (IEA-ETSAP, 2026) and Python programming language platforms.

### 1.3.2 Data inputs

The GEC Model is a data-intensive model covering the whole global energy system. Much of the data on historical energy supply, transformation and demand, as well as energy prices, is obtained from the IEA's own energy and economic databases. Additional data from a wide range of often sector-specific external sources are also used, in particular to establish the historical size and performance of energy-consuming stocks.

The formal base year for this year's projections is 2024, as this is the most recent year for which a complete picture of energy demand and production is available. However, we have used more recent data wherever available, and we include our 2025 estimates for energy production and demand in Annex A of the *World Energy Outlook 2026*. Estimates for 2025 are based on the IEA *Global Energy Review 2026* report (IEA, 2026b), in which data are derived from a number of sources, including the latest monthly data submissions to the IEA 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. Investment estimates include 2026 data, based on the IEA *World Energy Investment 2026* report (IEA, 2026c). Historical data for gross power generation capacity are drawn from the Power Plant Units database and the World Electric Power Plants database, both published by S&P Global Market Intelligence[1] (S&P Global, 2026); the International Atomic Energy Agency PRIS database (IAEA, 2026); and the Global Coal Plant Tracker and the Global Oil and Gas Plant Tracker databases, both published by Global Energy Monitor (GEM, 2026). Data on deployment and techno-economic performance of technologies used in different sector models include 2025 and estimates for 2026, such as data in the Global Hydrogen Review 2026 (IEA, 2026d) and the Global Electric Vehicle Outlook 2026 (IEA, 2026e).

For a summary of selected key data inputs – including macro drivers such as population, economic developments and prices, as well as techno-economic inputs such as fossil fuel resources and technology costs – please see the GEC Model key input dataset (IEA, 2026f).

### 1.3.3 Regional coverage and time horizon

The GEC Model covers the energy developments in the full global energy system up to 2050, with the capacity to extend beyond 2050 for some regions. Simulations are carried out on an annual basis, with hourly modelling for the power sector. The current version of the model provides results for 29 regions of the globe, of which 16 are individual countries. Several supply components of the model have further regional disaggregation: the oil and gas supply model has 113 regions and the coal supply model 34 regions.

### 1.3.4 Capabilities and features

The IEA's GEC Model offers unparalleled scope and detail about the energy system. Its essential purpose is to evaluate energy supply and demand, as well as the environmental impacts of energy use and the impacts of policy and technology developments on the energy system. Through long-term scenario analysis, the model can be used to explore possible futures related to the following main areas:

- **Global and regional energy trends**: Assessment of energy demand, supply availability and constraints, international trade and energy balances by sector and by fuel.

[1] The quarterly published S&P World Electric Power Plants database has been discontinued, with March 2023 the last edition. This product has been largely subsumed into the online S&P Power Plant Units database, which is published within the suite of datasets on the S&P Capital IQ Pro platform by S&P Global Market Intelligence. As a result of this migration, historical capacity differences may be observed, in particular for fossil-fuelled power plant, compared to the *WEO-2023* and earlier editions.

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- **Environmental impact of energy use**: $CO_2$ emissions from fuel combustion are derived from the projections of energy consumption. $CO_2$ process emissions are based on the production of industrial materials. $CH_4$ and $N_2O$ emissions are assessed for final energy demand as well as for energy transformation. Methane from oil and gas operations is assessed through bottom-up estimates and direct emissions measurements (see Global Methane Tracker). Local air pollutants are also estimated by linking the GEC Model with the GAINS model of the International Institute for Applied Systems Analysis (IIASA). The temperature outcomes of modelled scenarios are assessed using the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC).
- **Policy and technology developments**: The impact of policy actions and technological developments on energy demand, supply, trade, investments and emissions can be investigated by comparing scenarios.

Additionally, the GEC Model has multiple detailed features that either underlie or build on the analysis of broader energy trends. These include:

- **Technologies**: Detailed techno-economic characterisation of more than 800 clean energy technologies, including those still under development (at either prototype or demonstration stage) for different applications in heavy industries, long-distance transport and carbon dioxide removal, among other sectors.
- **People-centred analysis**: Detailed modelling of behavioural changes, energy sector employment, equity outcomes and energy affordability, among other implications for citizens.
- **Critical minerals**: Comprehensive analysis of projected demand and supply of critical minerals needed for the energy sector's transition.
- **Infrastructure**: Detailed modelling and analysis of energy infrastructure development needs and strategies, including electricity systems, fossil fuels, hydrogen-related fuels distribution and $CO_2$ transport options.
- **Variable renewables potential**: Detailed geospatial analysis of variable renewables potentials across the globe and modelling of the impact of exploiting them for hydrogen production.
- **Modern energy access**: Comprehensive modelling of the implications of and opportunities for providing energy access to all communities. This includes access to electricity and clean cooking facilities, and an evaluation of additional energy demand, investments and related GHG emissions.
- **Material efficiency**: Granular modelling of strategies along supply chains to make the use of materials, including steel, cement, aluminium, plastics and fertilisers, more efficient.
- **Investments**: Detailed modelling of overall energy sector and clean energy investments by sub-sector and technology areas, and comprehensive analysis of effective financing strategies. This includes investment requirements in fuel supply chains to satisfy projected energy demand and for demand-side technologies and measures (e.g. energy efficiency, electrification). Government spending is also tracked.
- **Decomposition**: Detailed mathematical framework to systematically analyse the specific contribution of different strategies to emissions or energy savings between scenarios and over time.

### *1.3.5 Connections with the international energy modelling community*

The development of the GEC Model benefits from expert review within the IEA and beyond, and the IEA works closely with colleagues in the global modelling community. For example, the IEA participates in and regularly hosts the International Energy Workshop and frequently interacts with the Integrated Assessment Modelling Consortium. The initial Net Zero Emissions by 2050 Scenario in 2021 was informed by discussions with modelling teams from across the world, including from China, the European Union, Japan, the United Kingdom, the United States, and the Intergovernmental Panel on Climate Change (IPCC).

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The IEA also has a long-standing history of working with researchers and modellers around the world as part of its Technology Collaboration Programmes (TCP) network. The TCPs support the work of independent, international groups of experts that enable governments and industries from around the world to lead programmes and projects on a wide range of energy technologies and related issues. The Energy Technology Systems Analysis Program (ETSAP) TCP, established in 1976, is among the longest-running TCPs. The ETSAP TCP supports policy makers in improving the evidence base underpinning energy and environmental policy decisions through energy systems modelling tools, including the TIMES modelling platform, and it brings together a unique network of nearly 200 energy modelling teams from approximately 70 countries.

The IEA's GEC Model also interacts closely with other internationally recognised models:

- The IEA uses the **Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC)**, developed and maintained by Climate Resource and often used by the IPCC for key publications, to inform its analysis of the impact of different greenhouse gas budgets on the average global temperature rise.
- IEA modelling results are coupled with the **Greenhouse Gas – Air Pollution Interactions and Synergies (GAINS)** model, developed and maintained by IIASA. This allows for detailed analysis of the impact of different IEA scenarios on air pollution.
- The **Aviation Integrated Model (AIM)**, developed by University College London, forms the basis for our modelling of the aviation sector.
- IEA modelling results have 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 spending on global GDP.
- The **Open Source Spatial Electrification Tool (OnSSET)** and **OnStove model**, two GIS-based optimisation tools developed as a result of a collaboration among several organisations, are used to inform the IEA's energy access modelling.

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# Cross-cutting inputs and assumptions

The GEC Model uses macro drivers, techno-economic inputs and policies as input data to design and calculate the scenarios.

Economic activity and population are the two fundamental drivers of demand for energy services in GEC Model scenarios. Unless otherwise specified, these are kept constant across all scenarios to provide a starting point for the analysis and facilitate the interpretation of the results.

Energy prices are another important input. The projections consider the average retail prices of each fuel in final uses, power generation and other transformation sectors. These end-use prices are derived from projected international prices of fossil fuels and subsidy and tax levels and vary by country.

## 2.1 Population assumptions

**Table 2.1 ▷ Population assumptions by region**

| | Compound average annual growth rate (%) | | | Population (million) | | | Urbanisation (share of population, %) | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2000-25 | 2025-35 | 2025-50 | 2025 | 2035 | 2050 | 2025 | 2035 | 2050 |
| North America | 0.7 | 0.5 | 0.4 | 517 | 544 | 572 | 80 | 82 | 87 |
| United States | 0.5 | 0.4 | 0.4 | 342 | 357 | 374 | 80 | 82 | 87 |
| C & S America | 0.7 | 0.5 | 0.3 | 531 | 559 | 577 | 82 | 84 | 87 |
| Brazil | 0.5 | 0.3 | 0.1 | 213 | 218 | 217 | 88 | 90 | 91 |
| Europe | 0.2 | -0.1 | -0.1 | 697 | 691 | 671 | 77 | 79 | 83 |
| European Union | 0.1 | -0.2 | -0.3 | 449 | 441 | 422 | 75 | 77 | 81 |
| Africa | 2.4 | 2.1 | 1.9 | 1 548 | 1 908 | 2 464 | 46 | 51 | 60 |
| Middle East | 1.9 | 1.5 | 1.3 | 286 | 332 | 391 | 73 | 74 | 78 |
| Eurasia | 0.5 | 0.3 | 0.4 | 243 | 252 | 266 | 65 | 66 | 68 |
| Russia | -0.1 | -0.3 | -0.2 | 143 | 139 | 135 | 75 | 77 | 81 |
| Asia Pacific | 0.7 | 0.4 | 0.3 | 4 369 | 4 557 | 4 677 | 52 | 55 | 63 |
| China | 0.2 | -0.3 | -0.5 | 1 413 | 1 371 | 1 257 | 67 | 73 | 90 |
| India | 1.0 | 0.8 | 0.6 | 1 464 | 1 579 | 1 680 | 36 | 39 | 43 |
| Japan | -0.3 | -0.6 | -0.6 | 123 | 116 | 105 | 92 | 94 | 96 |
| Southeast Asia | 0.9 | 0.6 | 0.4 | 699 | 740 | 773 | 54 | 60 | 68 |
| **World** | **1.0** | **0.8** | **0.6** | **8 192** | **8 843** | **9 618** | **58** | **61** | **67** |

Notes: C & S America = Central and South America. See Annex A for composition of regional groupings.

Sources: IEA analysis based on UN DESA (2025; 2024), World Bank (2026a), OECD (2026).

Rates of population growth for each GEC Model region are based on the medium-fertility variant projections contained in the United Nations Population Division report from 2024 (UN DESA, 2024). In the 2026 GEC modelling cycle, population rises from 8.2 billion in 2025 to around 9.6 billion in 2050. Population growth slows over the projection period, in line with past trends, from 1.2% per year in 2000-2025 to 0.8% in 2025-2035, due in large part to falling global fertility rates as average incomes rise.

Around two-thirds of the increase in the global population to 2050 is in Africa, underlining the importance of the African continent to achieving the world's Sustainable Development Goals (SDGs). More than one-fifth of the increase is in the Asia Pacific region, where India alone accounts for around 15% of the global growth. India has

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already been the world's most populous country since 2023, as China's population growth stalled and started to decline.

Estimates of the rural/urban split for each GEC Model region have been taken from (UN DESA, 2025), which is the latest available edition of the UN World Urbanization Prospects. This database provides the percentage of population residing in urban areas by country by year over the projection horizon. By combining these data with the UN population projections, we can calculate an estimate of the rural/urban split. In 2025, about 58% of the world population is estimated to be living in urban areas. This is expected to rise to 67% by 2050.

## 2.2 Macroeconomic assumptions

**Table 2.2 ▷ Average GDP growth assumptions by region**

| | Compound average annual growth rate | | | |
|---|---|---|---|---|
| | 2015-25 | 2025-35 | 2035-50 | 2025-50 |
| North America | 2.3% | 1.9% | 1.8% | 1.9% |
| United States | 2.4% | 2.0% | 1.8% | 1.9% |
| Central and South America | 1.2% | 2.6% | 2.0% | 2.2% |
| Brazil | 1.4% | 2.3% | 2.1% | 2.2% |
| Europe | 1.9% | 1.6% | 1.2% | 1.4% |
| European Union | 1.7% | 1.3% | 0.9% | 1.0% |
| Africa | 2.8% | 4.3% | 4.0% | 4.1% |
| South Africa | 0.6% | 1.7% | 2.3% | 2.0% |
| Middle East | 2.3% | 3.0% | 2.7% | 2.8% |
| Eurasia | 2.3% | 1.8% | 1.6% | 1.7% |
| Russia | 1.8% | 0.9% | 0.5% | 0.7% |
| Asia Pacific | 4.5% | 3.9% | 2.7% | 3.2% |
| China | 5.5% | 3.5% | 2.2% | 2.7% |
| India | 5.8% | 6.2% | 3.9% | 4.8% |
| Japan | 0.5% | 0.6% | 0.7% | 0.7% |
| Southeast Asia | 4.0% | 4.4% | 3.0% | 3.6% |
| **World** | **3.1%** | **3.0%** | **2.4%** | **2.6%** |

Note: Calculated based on GDP expressed in year-2025 US dollars in purchasing power parity terms.

Source: IEA analysis based on IMF (2026) and Oxford Economics (2026).

Out to 2030, our GDP assumptions at a country and regional level are based on the IMF World Economic Outlook (October 2026), with global GDP projected to grow by 3% annually over this period (IMF, 2026). After 2030, GDP growth assumptions are based on Oxford Economics forecasts (Oxford Economics, 2026) and the application of the Solow growth model. The Solow model estimates future GDP on a country and regional basis by accounting for labour supply, capital stock and total factor productivity (TFP). TFP growth reflects catch-up dynamics in lower-income countries and convergence towards advanced economy levels. In GEC Model 2026 scenarios, the global economy is assumed to grow by 2.6% per year on average over the period to 2050, with large variations by country, by region and over time.

We recognise that the speed, structure and selection of policy and regulatory mechanisms driving changes in the energy system will have broader economic effects, both positive and negative, across various countries and regions. However, 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.

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## 2.3 Prices

### 2.3.1 *International fossil fuel prices*

**Table 2.3 ▷ Fossil fuel prices by scenario**

| | | CPS | | STEPS | | ARC | | NZE | |
|---|---|---|---|---|---|---|---|---|---|
| **USD** (2025, MER) | 2025 | 2035 | 2050 | 2035 | 2050 | 2035 | 2050 | 2035 | 2050 |
| **IEA crude oil** (USD/barrel) | 68 | 85 | 106 | 75 | 70 | 72 | 62 | 34 | 26 |
| **Natural gas** (USD/MBtu) | | | | | | | | | |
| United States | 3.5 | 4.7 | 5.0 | 4.1 | 4.6 | 4.0 | 4.4 | 2.1 | 2.0 |
| European Union | 11.1 | 9.4 | 10.5 | 5.7 | 8.9 | 6.1 | 5.4 | 4.2 | 4.0 |
| China | 9.8 | 9.9 | 11.2 | 6.4 | 9.5 | 7.2 | 6.3 | 4.9 | 4.9 |
| Japan | 12.6 | 10.9 | 12.4 | 6.8 | 9.9 | 7.1 | 5.8 | 4.9 | 4.9 |
| **Steam coal** (USD/tonne) | | | | | | | | | |
| United States | 55 | 58 | 55 | 44 | 41 | 58 | 56 | 26 | 25 |
| European Union | 99 | 97 | 85 | 82 | 71 | 79 | 65 | 49 | 41 |
| Japan | 117 | 124 | 105 | 109 | 94 | 104 | 87 | 63 | 51 |
| Coastal China | 107 | 120 | 105 | 107 | 98 | 107 | 98 | 61 | 53 |

Notes: MBtu = million British thermal units; CPS = Current Policies Scenario; STEPS = Stated Policies Scenario; ARC = Additional Response Case; NZE = Net Zero Emissions by 2050 Scenario; MER = market exchange rate. The IEA crude oil price is a weighted average of import prices among IEA Member countries. Natural gas prices are weighted averages expressed on a gross calorific-value basis and exclude regasification charges. The US natural gas price reflects the wholesale price prevailing on the domestic market. Natural gas prices in the European Union and China reflect a balance of pipeline and liquefied natural gas (LNG) imports, while the Japan gas price is solely for LNG imports. LNG prices 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 costs. The coastal China steam coal price reflects a balance of imports and domestic sales, while the EU and Japanese steam coal prices are solely for imports. Wholesale prices exclude any emissions pricing applied at the point of use.

Source: IEA GEC Model 2026.

International prices for coal, natural gas and oil in the GEC Model reflect the price levels that are needed to stimulate sufficient investment in supply to meet projected demand. They are one of the fundamental drivers for determining fossil fuel demand and supply projections in all sectors and are derived through iterative modelling.

The supply modules calculate the production of coal, natural gas and oil that is stimulated under a given price trajectory, considering the costs of various supply options and the constraints on resources and production rates. If prices are too low to encourage sufficient production to cover global demand, the price level is increased, and energy demand is recalculated. The new demand resulting from this iterative process is again fed back into the supply modules until a balance between demand and supply is reached for each projected year.

The price trajectories do not attempt to represent the fluctuations and price cycles that characterise commodity markets in practice. The potential for volatility is ever present, especially in systems that are undergoing a necessary and profound transformation.

Fossil fuel price paths vary across the scenarios. In the Current Policies Scenario (CPS), rising oil demand and declining output from existing fields require continued investment in higher-cost supply, pushing prices upwards. In the Stated Policies Scenario (STEPS), slowing demand growth gives way to a slight decline, with prices rising more moderately before falling; substantial investment remains necessary to offset field declines. In the Additional Response Case (ARC), oil demand is below the STEPS level, while policies supporting viable domestic production, including tax and royalty reductions, further moderate prices. In the Net Zero Emissions by 2050

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Scenario, rapidly contracting oil demand drives prices sharply lower towards the costs of the most competitive producers, while strong policies prevent a demand rebound.

### 2.3.2 $CO_2$ prices

**Table 2.4 ▷ $CO_2$ prices in selected regions by scenario**

| USD (2025, MER) per tonne of $CO_2$ | 2035 | 2040 | 2050 |
|---|---|---|---|
| **Current Policies Scenario*** | | | |
| Advanced economies | 12 | 12 | 12 |
| Selected emerging market and developing economies** | 1.9 | 1.9 | 1.9 |
| Other emerging market and developing economies | < 1 | < 1 | < 1 |
| **Stated Policies Scenario*** | | | |
| Advanced economies | 26 | 30 | 47 |
| Selected emerging market and developing economies** | 3.8 | 4.6 | 6.2 |
| Other emerging market and developing economies | < 1 | 1.4 | 2.3 |
| **Net Zero Emissions by 2050 Scenario** | | | |
| Advanced economies | 180 | 205 | 250 |
| Selected emerging market and developing economies** | 125 | 160 | 200 |
| Other emerging market and developing economies | 20-50 | 25-85 | 40-180 |

*$CO_2$ prices are weighted averages across all covered energy sectors and countries within the region.

**Includes Argentina, Brazil, China, India, Indonesia and South Africa.

Notes: USD = United States dollar; MER = market exchange rate. Values are rounded.

Source: IEA GEC Model 2026.

$CO_2$ price assumptions are one of the inputs into the GEC Model, as the pricing of $CO_2$ emissions affects demand for energy by altering the relative costs of using different fuels. There are 87 direct carbon pricing instruments today, covering 58 countries and 42 subnational jurisdictions. Many others have schemes under development or are considering doing so. Alongside $CO_2$ pricing, all scenarios consider the effects of other policy measures, such as coal phase-out plans, efficiency standards and renewable targets. These policies interact with carbon pricing; therefore, $CO_2$ pricing is not the marginal cost of abatement, as it often is in other modelling approaches.

The CPS only considers enforced existing schemes as of 2026, at national and subnational level, covering electricity generation, industry, energy production sectors and end-use sectors, e.g. aviation, road transport and buildings, where applicable. It therefore excludes schemes yet to be implemented, and reforms to extend the coverage of existing ones and to phase out free allowances. The STEPS considers all existing or scheduled carbon pricing schemes and reforms. In the NZE Scenario, $CO_2$ prices cover all regions and rise rapidly across all advanced economies as well as in emerging economies with net zero emissions pledges, including Argentina, Brazil, China, India, Indonesia and South Africa. $CO_2$ prices are lower, but nevertheless rising, in other emerging economies such as in the Middle East, North Africa, Russia and other Southeast Asia. $CO_2$ prices are lower in all other emerging market and developing economies, as it is assumed they pursue more direct policies to adapt and transform their energy systems.

### 2.3.3 End-user prices

#### Fuel end-use prices

For each sector and GEC Model region, a historical representative price (usually a weighted average) is derived, taking into account the product mix in final consumption and price differences between countries within each GEC Model region. Scenario-specific assumptions on international wholesale price evolution are then applied to derive average pre-tax prices for coal, oil and gas over the projection period. Where applicable, excise taxes,

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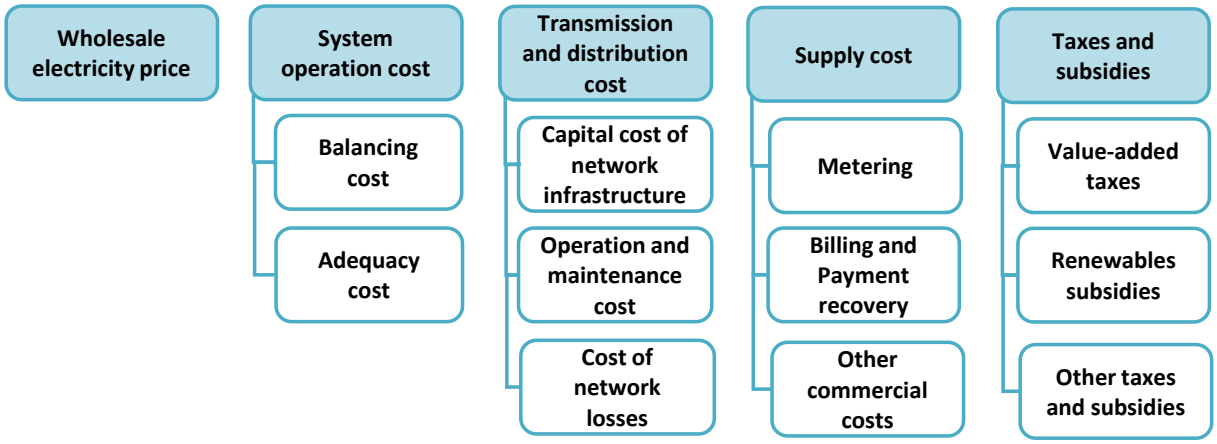
value-added tax rates, subsidies and $CO_2$ prices are included in the average post-tax prices for all fuels. In all cases, the excise taxes and value-added tax rates on fuels are assumed to remain unchanged over the projection period. Energy-related consumption subsidies, expressed as a percentage of the fuel price, remain constant in the CPS. In the other scenarios, they are gradually reduced over the projection period, though at varying rates across regions and scenarios. Governmental actions to shield consumers are also taken into account.

In the APS and the NZE Scenario, the international oil price drops in comparison to the STEPS due to lower demand for oil products. To counteract a rebound effect in the transport sector from lower gasoline and diesel prices, a $CO_2$ tax in the form of an increase in fuel duty is applied whenever it is necessary for ensuring that end-user prices are kept at least at the same level as in the STEPS. All prices are expressed in US dollars and assume no change in exchange rates over the projection period.

### *Electricity end-use prices*

The model calculates electricity end-use prices as a sum of the wholesale electricity price, system operation costs, transmission and distribution costs, supply costs, and taxes and subsidies.

**Figure 2.1 ▷ Components of retail electricity end-use prices**




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There is no single definition of wholesale electricity prices, but in the GEC Model, the wholesale price refers to the average price paid to generators for their output. For each region, wholesale electricity prices are derived under the assumption that all plants operating in a given year recover the full costs – i.e. fixed costs as well as variable costs – of electricity generation and storage. The key region-specific factors affecting wholesale prices are therefore:

- The upfront capital investment and financing costs of electricity generation and storage plants.
- The operation and maintenance costs of electricity generation and storage plants.
- The variable fuel cost of coal, natural gas, oil and other input fuels and, if applicable, the $CO_2$ cost of generation plants' output.

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 historical data. Taxes and subsidies are also taken from the most recent historical data, with subsidy phase-out assumptions incorporated over the outlook period in line with the relevant assumptions for each scenario.

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### *Fossil fuel subsidies*

The IEA measures fossil fuel consumption subsidies (IEA, 2025a) 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 prevail in a competitive market. However, estimates produced using the price-gap approach do not capture all types of interventions known to exist. Therefore, they tend to understate the impact of subsidies on economic efficiency and trade. Despite these limitations, the price-gap approach is a valuable tool for estimating subsidies and comparing subsidy levels across countries to support policy development (Koplow, 2009).

## 2.4 Policies

Underpinning the scenario analysis, an extensive effort is made to update and expand the list of energy and climate-related policies and measures that feed into our modelling. Assumptions about government policies are critical to this analysis and are the main reason for the differences in outcomes across the scenarios.

Two notable IEA policy tracking efforts provide input into the scenarios:

- **Global Energy Policies Hub:** The IEA's Global Energy Policies Hub provides a unique database on the current state of energy policy worldwide. This tracker inventories the most up-to-date policies for 85 countries in the IEA's Policies and Measures Database. It captures regulations, government spending programmes and trade policies by bringing together regular updates from the IEA's stand-alone Global Methane Tracker, critical mineral policy tracker and government energy spending tracker. This policy information has been collected from governments, partner organisations and IEA analysis. Governments have an opportunity to review the policy information periodically.
- **SDG 7 database:** The IEA is at the forefront of global efforts to assess and analyse the persistent deficit in energy access, providing annual country-by-country data on access to electricity and clean cooking (SDG 7.1). It also provides the main data source for tracking official progress towards SDG targets on renewables (SDG 7.2) and energy efficiency (SDG 7.3). The IEA is one of the appointed co-custodians for tracking global progress on SDG 7 alongside IRENA, UNSD, the World Bank and the World Health Organization (WHO).

A summary of key policy targets and measures by sector in selected countries and regions can be found in Annex B of *World Energy Outlook 2026*. The policies considered are additive across scenarios: measures listed under the STEPS supplement those in the CPS. The tables do not include all policies and measures; rather, they highlight the policies principally shaping global energy demand today. They are derived from an exhaustive examination of announcements and plans in countries around the world. Industry-led initiatives and manufacturing targets that are partially or fully met in the IEA scenarios are the final element making up Annex B.

### *Government energy spending policies*

The IEA has been monitoring government spending since April 2020, as part of its Government Energy Spending Tracker (formerly the Sustainable Recovery Tracker), which assesses the impact of sustainable recovery policies enacted by governments in response to the Covid-19 pandemic and the 2022 energy crisis. In 2025, the Agency enlarged the scope of its tracking to collect government earmarked budgets and actual disbursements with a wider scope of analysis, including energy affordability measures and fuel support. Since 2024, the detailed analyses of government energy spending can be found in the *State of Energy Policy* annual report.

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## 2.5 Techno-economic inputs

Incorporation of a diverse range of technologies is a key feature of the GEC Model. Extensive research is undertaken to update the range of technologies in the model, as well as their techno-economic assumptions.

The GEC Model includes the breadth of technologies that are available on the market today. Additionally, the model integrates innovative technologies and individual technology designs that are not yet available on the market at scale, by characterising their maturity and expected time of market introduction. For each sector and technology area, new project announcements and important technological developments are tracked in databases that are regularly published.

The modelled scenarios are informed by a similarly detailed technology tracking process. For instance, the project planning and financing status is an important consideration for whether projects are reflected in the STEPS or in the CPS. For technology development and the time to bring new technologies to markets, the scenarios assume a different pace of progress as the support and degree of international co-operation on clean energy innovation increase with ambition on decarbonisation.

The following databases are particularly relevant for the definition of the different scenarios:

- Clean innovative technologies tracking:
  - **Clean Technology Guide: Interactive** database that tracks the technology readiness level (TRL) of almost 600 individual technology designs and components across the whole energy system that contribute to achieving the goal of net zero emissions. The guide is updated every year.
  - **Clean Energy Demonstration Projects Database: Launched** in 2022 and updated every year, this provides more detailed tracking of the location, status, capacity, timing and funding of over 500 demonstration projects across the energy sector.
- **Hydrogen Production and Infrastructure Projects Database: Covers** all projects commissioned worldwide since 2000 to produce hydrogen for energy or climate change mitigation purposes.
- **CCUS Projects Database: Covers** all large-scale $CO_2$ capture, transport, storage and utilisation projects (at least 100 000 tonnes $CO_2$ per year) commissioned or in planning worldwide across sectors.
- **Global EV Outlook: Annual** publication that identifies and discusses recent policy and market developments in electric mobility across the globe. It is developed with the support of the members of the Clean Energy Ministerial Electric Vehicles Initiative.

Technology costs are an important input to the model. All costs represent fully installed or delivered technologies, not solely the module cost, unless otherwise noted. Installed or delivered costs include engineering, procurement and construction costs to install the module. Some illustrative examples include the following:

- **Iron-based steel** production costs display a range considering technology and regional differences, e.g. capital expenditure, operating expenditure and learning rate, and differentiate between conventional and innovative production routes. Levelised cost of production includes estimated iron ore prices, carbon prices and fuel subsidies differentiated by region and scenario, and it is weighted by regional deployment. Conventional routes are blast furnace-basic oxygen furnace (BF-BOF) and direct reduced iron-electric arc furnace (DRI-EAF). The innovative routes are BF-BOF with carbon capture, utilisation and storage (CCUS), DRI-EAF with CCUS, and 100% electrolytic hydrogen-based DRI-EAF.
- **Vehicle** costs reflect production costs, not retail prices, to better capture the declines in total cost of manufacturing. They represent a global average, evolving in line with the regions' roles in the global market and their respective production costs.

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- **Electrolyser** costs reflect a weighted average among different electrolysis technologies. The lower value for hydrogen electrolysers refers to China and the upper one to the rest of the world.
- **Fuel cell** costs are based on stack manufacturing costs only, not installed or delivered costs. The costs provided are for automotive fuel cell stacks for heavy-duty vehicles.
- **Utility-scale stationary battery** costs reflect the global average installed costs of all battery systems rated to provide maximum power output for two-, four- and eight-hour periods.

**Table 2.5 ▷ Costs for selected technologies by scenario**

| | | Current Policies Scenario | | Stated Policies Scenario | | Net Zero Emissions by 2050 Scenario | |
|---|---|---|---|---|---|---|---|
| | 2025 | 2035 | 2050 | 2035 | 2050 | 2035 | 2050 |
| **Levelised cost of iron-based steel production** (2025 USD/t) | | | | | | | |
| **Conventional** | | | | | | | |
| Lower range | 520 | 530 | 520 | 520 | 510 | 550 | 690 |
| Upper range | 640 | 630 | 620 | 650 | 690 | 790 | 820 |
| **Innovative** | | | | | | | |
| Lower range | N/A | 960 | 900 | 890 | 870 | 690 | 700 |
| Upper range | N/A | 1010 | 940 | 1030 | 980 | 830 | 870 |
| **Vehicles** (2025 USD/vehicle) | | | | | | | |
| Hybrid cars | 17 900 | 16 200 | 16 100 | 16 100 | 16 000 | 15 900 | 15 800 |
| Battery electric cars | 20 300 | 16 600 | 15 800 | 16 100 | 15 100 | 15 500 | 14 600 |
| **Hydrogen** (2025 USD/kW) | | | | | | | |
| **Hydrogen electrolysers** | | | | | | | |
| Lower range | 550 | 440 | 390 | 420 | 390 | 330 | 310 |
| Upper range | 2 500 | 1 780 | 1 550 | 1 750 | 1 530 | 1 370 | 1 230 |
| **Fuel cells** | | | | | | | |
| Trucks | 360 | 250 | 230 | 240 | 200 | 150 | 80 |
| **Utility-scale stationary batteries** (2025 USD/kWh) | | | | | | | |
| 2-hour batteries | 195 | 140 | 110 | 135 | 105 | 135 | 110 |
| 4-hour batteries | 190 | 130 | 100 | 125 | 100 | 125 | 100 |
| 8-hour batteries | 155 | 115 | 85 | 115 | 85 | 115 | 95 |

Notes: t = tonne; kW = kilowatt; kWh = kilowatt-hour.

Sources: IEA analysis; BNEF (2025); NREL (2021); Financial Times (2020); JATO (2021); S&P Global Mobility (2024) JRC (2018a).

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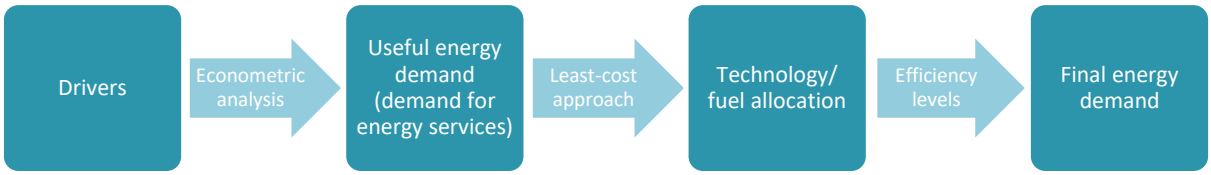
All 29 regions are modelled in considerable sectoral and end-use detail. Specifically:

- **Industry** is composed of five energy-intensive and eight non-energy-intensive sub-sectors.
- **Buildings** is separated into residential and services buildings, with six end-uses modelled separately.
- **Transport** is separated into nine modes, with considerable detail provided for most of them.
- **Agriculture** modelling reflects the range of fuels and energy-consuming applications in the sector.

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 sector.

Demand-side drivers, such as steel production in industry or household size in buildings, are estimated econometrically based on historical data and on socioeconomic drivers (such as GDP and population). 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 area in buildings. To take into account expected changes in structure, policy or technology, a wide range of technologies that can satisfy each specific energy service are integrated in the model. End-user fuel prices and technology costs play an important role in determining the distribution of technologies and fuels, although real-world non-cost influences also play a role. Accounting for the efficiency level of all end-use technologies gives the final energy demand for each sector and sub-sector (Figure 3.1).

**Figure 3.1 ▷ General structure of demand modules**




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## 3.1 Useful energy demand

**Useful energy** is the portion of energy in a system that performs the intended task. In other words, useful energy is the part of the input energy that is converted into the desired output form, accounting for end-use conversion efficiencies. For example, in transport, this is the energy that moves the vehicle and enables the provision of mobility services; in buildings lighting, this is the light produced by the light bulb; or in industry steelmaking factories, the chemical and thermal energy required to reduce iron ore into liquid iron metal.

**Useful energy measures energy services provided by modern energy sources. It does not include** non-energy use or traditional use of biomass, while they are both reported at the final consumption level, i.e. in the IEA's Energy Data Centre (EDC) energy balances.

### *3.1.1 Why do we model useful energy demand?*

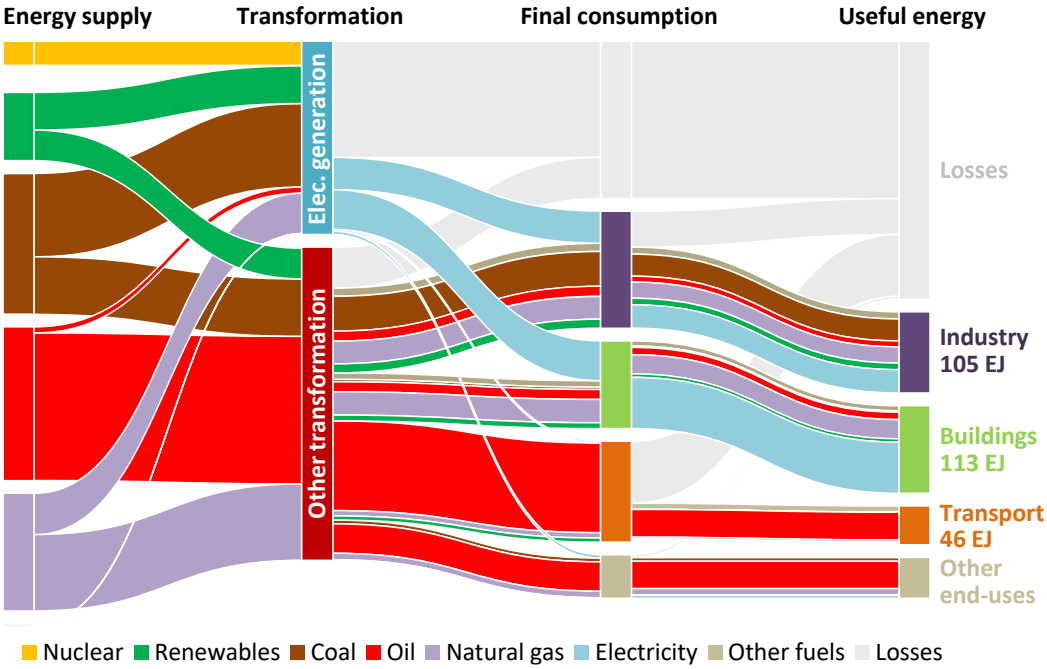
Consumers derive utility, or satisfaction and well-being, from the energy services delivered by equipment that uses energy products like gasoline, natural gas or electricity. Examples include movement enabled by gasoline in a vehicle, heat generated by natural gas in a boiler, or cooling provided by electricity in an air conditioning unit.

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However, estimating the energy consumption is far easier than calculating the resulting energy services, which requires engineering analysis. For this reason, energy balances use final consumption of energy products as the last step in the energy value chain and do not go a step further by including the process of converting these products into useful energy (or service demand) as well as estimating the resulting losses.

But useful energy demand is essential to understand energy demand trends across the world. It is the first energy-based measure of end-user needs and directly relates to sectoral activity, GDP or population. Starting from today's useful energy demand, socioeconomic drivers project future useful demand, which is met by a stock of equipment shaped by policy choices in each scenario. Final consumption is derived from the fuel mix and performance level of the equipment stock. This approach, in which useful energy demand is at the core of end-use sector modelling, has been developed and used by the energy modelling community (Brockway, 2024; IIASA, 2023a; LEAP, 2026; Paoli & Cullen, 2023; Mousavi, 2019).

**Figure 3.2 ▷ Global energy flows from primary to useful energy by energy carrier and sector, 2025**




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*The global energy system takes primary energy flows and converts them to useful energy, but substantial heat losses take place during the process*

Notes: EJ = exajoule. Elec. generation = electricity generation. Other transformation includes heat production and other energy sector. Other fuels include district heat, hydrogen and others. Other end-uses include non-energy use and agriculture. Traditional use of biomass is not included, and losses are shown on a net basis.

The GEC Model, which underpins the World Energy Outlook, is a bottom-up, stock-based model that assesses final energy demand across sectors, end uses and regions. It links activity drivers to existing stocks of vehicles, industrial capacity, appliances and buildings, and it represents more than 200 end-use technologies, allowing it to capture technology choices, fuel use and efficiency levels. Combined with assumed technology efficiencies, this representation enables the assessment of useful energy for each end-use or sub-sector covered. Useful energy and final consumption compare as follows:

- When the efficiency is lower than 1, the equipment loses energy in the conversion process and useful energy is lower than final consumption. Useful energy therefore refers to the actual services enjoyed by the user of a certain technology or service, after considering such losses.

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- Equipment and devices powered by electricity are typically more efficient than those powered by other fuels that require combustion. Combustion engines convert heat into motion and are fundamentally limited by the second law of thermodynamics: entropy must increase, requiring part of the energy to be rejected as waste heat. An internal combustion engine vehicle, for example, converts only 25-30% of the energy contained in gasoline into motion. Electric motors convert electricity directly into mechanical motion, avoiding the heat-engine efficiency limitation. As a result, electric cars are typically two to four times more efficient than comparable vehicles powered by fossil fuels.
- Heat pumps are even more efficient because they transfer heat from the surrounding environment rather than generating it from fuel combustion. Air conditioners operate likewise, and more energy is exchanged between the environment and the user than consumed to enable the transfer. Therefore, useful energy is higher than final consumption. Heat pumps are around three to five times more efficient than boilers, and in space cooling, useful demand is three to six times higher than electricity consumed.
- Useful energy demand directly reflects consumer needs. In aggregate, it is driven by activity (for instance, a growing number of households, or rising incomes leading to higher mobility needs), but also improvements in buildings insulation or material efficiency in industry, which reduce useful energy demand. For the same indoor temperature, useful energy demand is lower in well-insulated buildings.

### *3.1.2 Useful energy demand modelling principles*

Useful energy demand modelling links activity, final consumption and equipment performance. Although the detailed calculations depend on the service being provided, the framework can be summarised in the following methodological steps:

1. **Energy services and activity variables.** Each energy service is associated with an activity variable in a specific unit. Historical activity data provides the starting point for projections linked to socioeconomic drivers, including GDP, population and urbanisation. This establishes how energy services evolve over time, separately from the technologies used to meet them.
2. **Equipment stocks, historical useful energy and intensities.** Our models represent the historical composition and performance of the equipment stock, distinguishing technologies, end uses and energy carriers at the regional level. Historical final energy consumption is combined with appropriate conversion efficiencies to estimate useful energy demand. The efficiency assumptions reflect the service provided, the technology mix and the conversion stages between energy input and useful output, drawing on stock data and energy balances. Historical useful energy demand is compared with the relevant activity variable to compute useful demand intensities, per unit of activity.
3. **Useful energy demand and equipment performance.** Activity variables, useful energy demand intensities and stock composition are projected based on sector-specific principles. Factors influencing projections include income, energy prices, environmental conditions and changes in the energy requirements of the activity itself. The stock turnover, along with scenario assumptions, affects technology deployment, performance standards and future conversion efficiencies. Future useful energy demand and equipment performance determine final energy consumption.

### *3.1.3 Buildings*

The buildings module applies the shared modelling principles to individual end uses, with specific treatments for thermal services, lighting and appliances (Priesmann et al., 2021; Gouveia et al., 2012). The activity–intensity relationship is expressed as follows:

$$End\ use\ useful\ energy\ demand = Activity\ variable \times intensity$$

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### *Historical useful energy demand*

For each end use, useful energy intensity is expressed relative to a corresponding activity variable, such as space heating demand per unit of floorspace. Buildings activity is projected econometrically based on the common socioeconomic variables described above, but the projection also accounts for urbanisation rates and access rates to modern energy. The end-use-specific adjustments are described below.

Calibration of historical data distinguishes equipment types within each end use and fuel. Equipment ownership data inform the technology mix, including the share of heat pumps within electricity-based heating equipment. Combined with total stock evolution and energy balances, this data establishes an average efficiency for each region, end use and fuel. Applying these efficiencies to consumption from the balances provides the historical useful energy demand used for end-use intensities.

Unlike heating and cooling, lighting and most appliances do not deliver a service to consumers through thermal energy transfers, but rather through luminosity or motion (such as most cleaning appliances). To keep a practical metric that can be combined across different end uses, we define standard intensity levels that correspond to the unit energy consumption of the best available technologies sold today. Efficiency levels in any given year and scenario are computed by comparing the equipment unit energy consumption with this standard value for appliances or light bulbs of an equivalent capacity.

| End-use | Average stock efficiency across regions in 2025 | End-use | Average stock efficiency across regions in 2025 |
|---|---|---|---|
| Space heating | 80%-95% | Refrigeration | 15%-30% |
| Water heating | 70%-90% | Brown appliances | 25%-35% |
| Cooking | 50%-65% | Washing | 20%-40% |
| Space cooling | 250%-620% | Drying | 15%-30% |
| Lighting | 40%-50% | Dishwashing | 20%-35% |

### *Projected useful energy demand: prices, income, climate and insulation*

Buildings useful energy intensities are projected using end-user fuel price elasticities and per capita income elasticities, applied to changes in average prices and incomes over time. This methodology applies across all buildings end uses, but it needs further refinements for space heating and space cooling, which interact more strongly with other elements of the energy system.

For space heating and space cooling, intensity projections are also adjusted for historical variations in temperature, and the improvements in buildings energy performance associated with new construction or renovations.

Historical energy demand for space heating and space cooling is combined with historical heating and cooling degree-day data to normalise projections of space heating and space cooling energy demand, removing the impacts of year-on-year volatility in useful energy demand. The impact of climate change on space heating and space cooling demand is accounted for in the model as well, based on the anticipated change in heating and cooling degree-days in each region and under each scenario's temperature pathway. These projections are based on climate modelling conducted by Climate Resource, building on emissions trends in each IEA scenario and ensuring overall consistency between cooling, heating, emissions and climate.

Space heating and space cooling useful energy demand is computed for buildings upon their construction, based on the average energy performance of new buildings at the time of construction. New buildings in the model are constructed as either compliant with building energy codes, non-compliant, or zero-carbon-ready buildings. The share of each category of newly constructed floorspace is determined based on the scope and stringency of building energy codes, an assessment of compliance and enforcement mechanisms, and estimates of irregular settlements and informal construction in the region. This choice, as well as the climatic zone and the year of construction, influences the building's useful energy demand. The useful energy demand of a building in the

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model can also be influenced by retrofitting: an existing building can be retrofitted to improve its energy performance, so that the building complies with existing regulation or becomes zero-carbon-ready. The projections of the shares of each type of new building and retrofit depend on the policy assumptions underlying each scenario. Retrofitting a building extends its lifetime, influencing both the need for new constructions and the associated demand for construction materials.

The total useful energy demand to be met by space heating or cooling equipment is therefore the sum of the useful demand across the different vintages of buildings, determined by the year of construction, and across the five categories of buildings (non-compliant, compliant, zero-carbon-ready, retrofit to compliant, retrofit to zero-carbon-ready). Improvements in the performance of building envelopes (either via more efficient new constructions or via retrofits) shift buildings from one category to another and thereby reduce the total useful energy demand for space heating and space cooling that remains to be met by heating or cooling equipment.

### *3.1.4 Industry*

Useful energy is assessed in line with the three modelling approaches taken in the industry model.

#### *Energy-intensive industrial commodities*

This concerns the technology-rich bottom-up modelling of iron, crude steel, ethylene, propylene, aromatics, ammonia, methanol, alumina, clinker, cement, aluminium, pulp and paper.

The approach is to select the least energy intensive of the existing best available technologies – from a final consumption point of view – and to assume it is deployed as of today in all regions. It also considers whether the industrial output is primary, i.e. made from raw materials, or secondary, made from scrap, to better reflect material availability constraints.

With this methodology, useful energy assessment is independent of technological choice and is closer to the thermodynamic energy requirements for industrial production. The table below summarises the technical assumptions for this part of the module.

| | | Energy input (GJ/t) | |
|---|---|---|---|
| **Commodity** | **Technology** | **Thermal** | **Electric** |
| Iron making | $H_2$-DRI (BAT) | 7.57 | 1.20 |
| Crude steel – primary | DRI-EAF (BAT) | 1.44 | 1.68 |
| Crude steel – secondary | Scrap-based – EAF (BAT) | 0.23 | 1.94 |
| Ethylene | Mixed-feed cracker (BAT) | 0.00 | 0.31 |
| Propylene | PDH (BAT) | 8.90 | 0.10 |
| Aromatics | Catalytic cracking (BAT) | 0.00 | 0.00 |
| Ammonia | Steam methane reforming (BAT) + Haber-Bosch (BAT) | 13.50 | 0.30 |
| Methanol | Catalytic hydrogenation (BAT) | 10.10 | 0.30 |
| Clinker | Dry kiln (BAT) | 2.90 | – |
| Cement | Dry kiln (BAT) | – | 0.25 |
| Alumina | Bayer process (BAT) | 2.07 | 2.07 |
| Aluminium – primary | Hall-Heroult with inert anode (BAT) | 0.65 | 50.12 |
| Aluminium – secondary | Scrap-based – Furnace (BAT) | 2.01 | 0.45 |
| Pulp – recovered | BAT | 0.58 | 1.10 |
| Pulp – chemical | BAT | 1.70 | 0.60 |
| Pulp – mechanical | BAT | 2.10 | 1.50 |
| Paper – graphic | BAT | 1.90 | 1.10 |
| Paper – household | BAT | 4.00 | 2.40 |
| Paper – packaging | BAT | 1.80 | 1.70 |
| Paper – other | BAT | 2.10 | 1.70 |

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#### *Other energy-intensive industries*

In the industry part of the GEC Model, each energy-intensive sector has a sub-sector that is modelled as a residual and is called "other", e.g. Non-metallic minerals = Cement + Other non-metallic minerals. This "other" sector is modelled with a top-down approach, i.e. based on energy intensity and fuel shares.

The methodology to assess useful energy is the following:

1. For historical years and the base year, we compute useful energy demand as final energy (fuel) multiplied by thermal efficiency (fuel).
2. For projection years, we compute total useful energy using the growth rate of total final energy demand of the "other" sector.
3. Useful energy demand by fuel is then computed using the fuel shares.

#### *Non-energy-intensive industries*

The non-energy-intensive industries module computes useful energy demand by end-use, i.e. thermal, mechanical, lighting and other. The first step is to allocate historical energy consumption by sub-sector and fuel across end-use using historical end-use shares from the literature (EIA, 2025).

The historical energy input to each end-use is then converted into useful energy by applying base-year efficiency factors from (IIASA, 2023a), (LEAP, 2026) and (Paoli & Cullen, 2023):

- heating efficiency by technology and temperature level
- cooling efficiency (COP)
- lighting efficiency (luminous efficacy proxy)
- mechanical efficiency by motor class and size.

### *3.1.5 Transport*

Transport activity, commonly expressed in passenger-kilometres or tonne-kilometres, is widely referred to in the transport literature as transport service demand. Future transport activity trends evolve based on socioeconomic drivers, including GDP, population and urbanisation rates. Energy intensity per unit of transport activity reflects historical trends, powertrain technologies and fleet turnover. Calculations are differentiated by region, transport mode and energy carrier. Transport useful energy is defined as the tractive energy available to meet mobility needs. Final consumption is converted into this measure using tank-to-wheel (TTW) efficiency (Vossier et al., 2026):

$$End\ use\ useful\ energy\ demand\ (fuel) = Final\ energy\ (fuel) \times TTW\ Efficiency\ (fuel)$$

The tractive energy delivered to the wheels or propulsion system is subsequently used to meet the energy requirements associated with vehicle movement. These include overcoming rolling resistance, aerodynamic or hydrodynamic drag, road or route gradients, and vehicle acceleration and deceleration (Jerrelind et al., 2021). Importantly, all these components contribute to providing the underlying mobility service.

TTW efficiency includes the following components:

- **Engine efficiency:** Assumptions for the efficiency of the vehicle engine (Global Fuel Economy Initiative, 2021).
- **Drivetrain or propulsion efficiency:** Assumptions for the efficiency of the drivetrain or propulsion system in converting the energy supplied by the engine or powertrain into useful mechanical or propulsive energy (Change Energy Services and Pollution Probe, 2021).

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The useful energy calculation is defined as follows:

- Throughout the historical and projection periods:

$$Useful\ energy\ demand\ (fuel) = Final\ energy\ (fuel) \times Efficiency^{1}\ (fuel)$$

  Transport efficiency assumptions reflect the purpose of fuel use and are differentiated by technology within each transport mode. The coverage includes nine different energy carriers and five transport modes: road (50 technology combinations), rail (6), aviation (3), navigation (6) and other transport.

  For projection years, scenario-specific assumptions capture improvements in engine and drivetrain or propulsion efficiency for each energy carrier and transport technology (JRC, 2017) (JRC, 2023).

| Technology | Average efficiency across regions today |
|---|---|
| Gasoline vehicle | 20%-25% |
| Hybrid vehicle | 30%-40% |
| Diesel vehicle | 25%-35% |
| Battery electric | 85%-90% |
| Hydrogen vehicle | 40%-50% |

## 3.2 Industry

Industry is the most energy-consuming and $CO_2$-emitting end-use sector. It accounts for about 40% of total useful energy demand, around the same share of total final consumption, and around 45% of $CO_2$ emissions (including emissions from electricity and heat). The industry model covers five energy-intensive sectors – accounting for 70% of global industry energy demand:

- iron and steel, with technology-rich modelling of iron and steel production
- chemicals, with technology-rich modelling of ammonia, methanol and high-value chemicals production
- non-metallic minerals, with technology-rich modelling of cement production
- non-ferrous metals, with technology-rich modelling of alumina and aluminium production
- paper, pulp and printing, with technology-rich modelling of pulp production and of paper production by paper type.

It also covers eight non-energy-intensive sectors: construction; food and tobacco; machinery; mining and quarrying; textile and leather; transportation equipment; wood and wood products; and other industry not specified elsewhere.

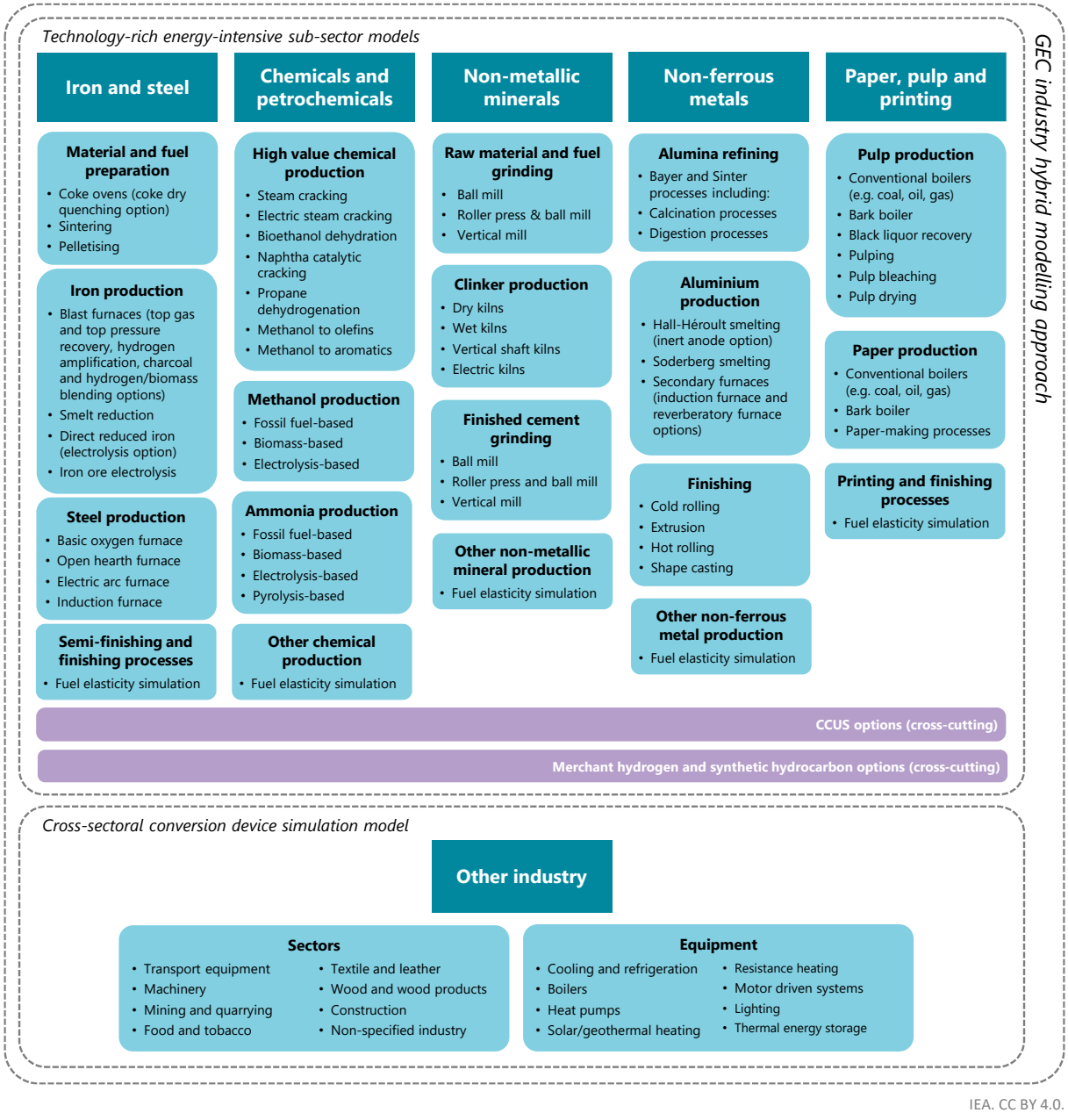
The industry sector model combines the strengths of both simulation and optimisation models into a single simulation framework, with its constraints and input parameters informed by periodic model runs of the former ETP TIMES optimisation framework, among other things.

[1] This factor captures the losses associated with engine and drivetrain or propulsion inefficiencies.

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### 3.2.1 Industry model coverage and approach

**Figure 3.3 ▷ Major categories of technologies by end-use sub-sector in industry**




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Note: CCUS = carbon capture, utilisation and storage.

For the purposes of the GEC industry model, the industrial sector includes International Standard Industrial Classification (ISIC) Divisions 7, 8, 10-18, 20-32 and 41-43, and Group 099, covering mining and quarrying (excluding mining and extraction of fuels), construction and manufacturing. This coverage follows the structure of the IEA Energy Balances and includes all the industry components of total final consumption. Chemical feedstock (a component of non-energy use) and blast furnace and coke oven energy use (both transformation and own use) are also included within the boundaries of industry. Final industrial energy consumption includes all electricity used in industrial processes, including that generated onsite (e.g. via captive combined heat and power units). Thus, fuel used to generate electricity onsite is excluded from that reporting to avoid double

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counting, and this fuel is accounted for in the transformation sector. Aside from petrochemical feedstock, other non-energy use is not included in the GEC Model's industry sector boundary, but rather it is modelled as a separate category in the same framework.

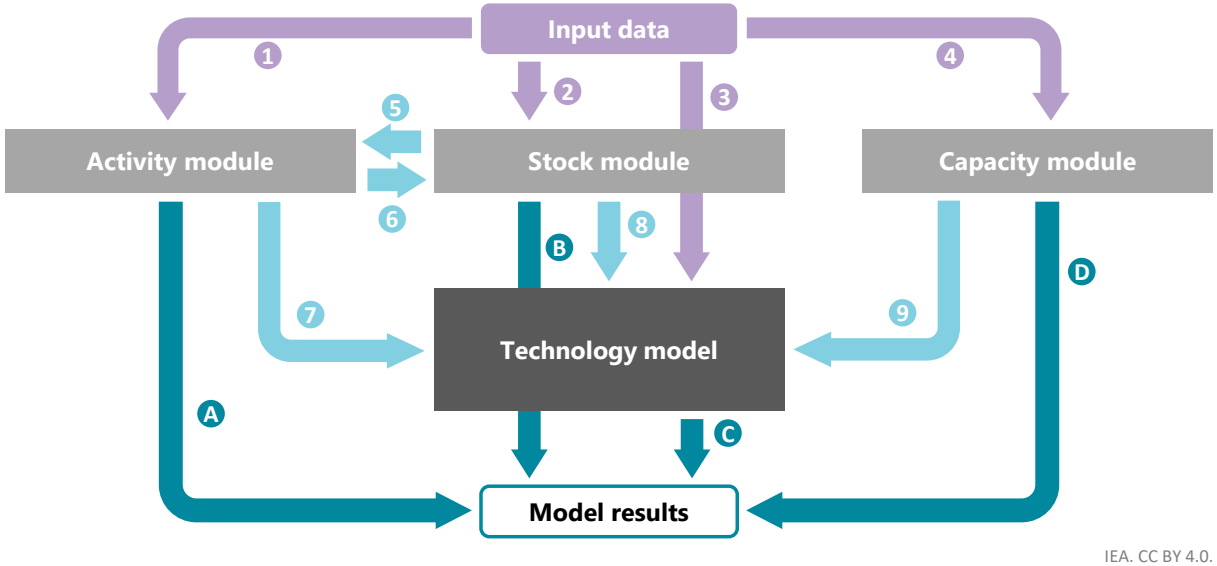
The industry sector is modelled using a hybrid approach (Figure 3.3). Technology-rich simulation models are used for five energy-intensive sub-sectors or components thereof (iron and steel; primary chemicals within chemicals and petrochemicals; cement within non-metallic minerals; aluminium within non-ferrous metals; paper, pulp and printing). The remaining non-energy-intensive industry sub-sectors (construction, mining and quarrying, transport equipment, machinery, food and tobacco, wood and wood products, textile and leather, and industry not elsewhere specified) are modelled using a cross-cutting conversion device simulation approach. For the residual components of the five energy-intensive sub-sectors (chemicals besides primary chemicals, non-metallic minerals besides cement, non-ferrous metals besides aluminium, downstream finishing processes in the iron and steel sector, and printing and residuals of pulp and paper production in the paper, pulp and printing sector), a cross-cutting approach similar to that for the non-energy-intensive sub-sectors is applied.

The five energy-intensive sub-sector models characterise the energy performance of process technologies at the process unit level (e.g. coal blast furnace, naphtha steam cracker). The cross-cutting simulation model for the remaining industry sub-sectors characterises the stock of the main conversion devices (e.g. motors, heating equipment) used to provide various energy services required during the production of thousands of materials and products. See the subsections below for more information on the approaches taken for each of these components of the GEC industry model.

### *3.2.2 Energy-intensive industries*

For each of the five energy-intensive industry sub-sectors, the modelling framework consists of a series of interacting sub-modules and a core technology model (see Figure 3.4). The sub-modules consist of an activity model, a stock model and a capacity model.

**Figure 3.4 ▷ Industry sector model internal module structure and key data flows**




Notes: Internal industry model flows: 1) Historical production, population projection, industry value-added projection; 2) End-use demand, product lifetimes, process yields, recycling and reuse rates; 3) Energy and raw material intensities, energy prices, CAPEX and operational expenditures (OPEX), lifetimes, technology deployment constraints, $CO_2$ emissions reduction trajectory; 4) Historic and planned capacity, lifetimes, refurbishments; 5) Consumption projections; 6) Material stocks saturation, material efficiency factors; 7) Production projections including trade; 8) Scrap availability; and 9) Residual capacity. Model results: A) Material production; B) Material stocks saturation; C) Energy consumption, $CO_2$ emissions, technology shares, investments; and D) Capacity installed, added and retired.

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The activity drivers for each sub-sector of the GEC industry model are tonnages of material produced in a given scenario at a given point in time. Activity modelling is handled similarly for all energy-intensive industry sub-sectors. Demand for materials is projected through interaction between an activity model and a stock model, together with modelling of material efficiency strategies. The activity model uses country-level historical data on material consumption to calculate demand per capita and then projects forward total demand using population projections and industry value-added projections (both sub-sector and total industry value added). The industry value-added projections inform the change in demand per capita.

The demand projections from the activity model feed into the stock model, which uses bottom-up material demand inputs from the buildings, transport and supply modules, and complementary assumptions about other end-product shares and lifetimes to calculate the implied build-up of material stocks. Stock saturation in the stock model in turn informs per capita material demand saturation in the activity model through a series of iterations.

Material efficiency strategies across value chains are also modelled. This modelling work builds mainly on the literature and previous IEA publications relating to material efficiency (IEA, 2019). Strategies considered include:

- **Design stage: Light-weighting** (producing the same product with a lower average mass per product), design for future material savings (modular design to enable material use reduction, design for recyclability).
- **Construction and manufacturing: Increased** yields (reducing the losses in semi-manufacturing and manufacturing), reduced materials waste (more careful construction practices and material handling).
- **Use: Longer** lifetimes (refurbishing buildings for other uses, reusing components for particular products), more intensive use of products (for example car sharing or using a building for a larger share of the day).
- **End-of-life: Direct** materials reuse (use of post-consumer materials – without re-melting in the case of metals – for the same or other applications), recycling (increased collection, improved sorting, and development of advanced recycling technologies).

Those strategies occurring in the other end-use sectors (e.g. building lifetime extension, vehicle light-weighting) are fed into the activity modelling via bottom-up demand estimates, while material efficiency strategies within the industry boundary (e.g. manufacturing yield improvements, direct reuse and recycling) are modelled within the stock model. These latter strategies lead to reduced material demand, which is fed into the activity model via a material efficiency factor. The resulting activity projections from the activity model and scrap availability (including semi-manufacturing, manufacturing and post-consumer scrap) from the stock model feed into the main technology model.

Material trade for steel, aluminium and ammonia (for final or intermediate products) between model regions is modelled through the IEA's Manufacturing and Trade (MaT) model. This projects trade flows based on the optimisation of overall manufacturing and trade costs under different scenarios to 2050. More information on the MaT model methodology and the latest information on scope and input data are included in the forthcoming edition of the Energy Technology Perspectives report. For other materials, trade is not modelled endogenously in the technology model, but rather it is reflected in the activity projections developed in the activity and stock models. Apart from specific instances in which announced policies or projected energy price signals provide relevant evidence to the contrary, trade patterns in material production and consumption are projected to follow current trends. Regional material production and demand are consistent with these projections of net trade patterns.

The capacity model contains data on historical and planned plant capacity additions and retrofits by plant type. Using assumptions about investment cycles, it calculates plant refurbishments and retirements. The resulting remaining capacity informs the main technology model. The capacity model also provides projections on the average age of plants at a given time and allows calculation of investment requirements.

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The main technology model of each sector consists of a detailed representation of process technologies required for relevant production routes, including both primary and secondary (from scrap or recycled material) production. Energy use and technology portfolios for each country or region are characterised in the base year using relevant energy use and material production statistics. Throughout the modelling horizon, demand for materials (as dictated by the activity model outputs) is met by technologies and fuels, whose shares are informed by announced projects, policies and support schemes, real-world technology progress and the previous ETP TIMES optimisation model. That model uses a constrained optimisation framework, with the objective function set to make choices that minimise overall system cost (comprising both energy costs and investments).

Changes in the technology and fuel mix, as well as efficiency improvements, are in part driven by a combination of exogenous assumptions on the penetration and energy performance of best available technologies, constraints on the availability of raw materials (such as scrap availability according to the stock model outputs), techno-economic characteristics of the available technologies and process routes, and assumed progress on demonstrating innovative technologies at commercial scale. The results are sensitive to assumptions about how quickly physical capital is turned over (including retirements of existing capacity according to the capacity model outputs) and about the relative costs of the various technology options and fuels. A given scenario can also be subject to a $CO_2$ emission trajectory that the model must adhere to. Model outputs include energy consumption, heat by temperature level, fuel combustion and process $CO_2$ emissions both emitted and captured, technology shares, raw materials and intermediate industrial materials flows, and investment requirements.

Some industrial sectors produce and use “onsite” hydrogen within the industrial facility, such as for specific ammonia, methanol or iron-based steel production processes. This hydrogen is not reported in standard energy balances, but it is reported as fossil fuel or electricity depending on whether it is produced via steam reforming or water electrolysis. Accounting for this hydrogen, which is necessary to build the global hydrogen balance , is performed in a dedicated hydrogen module. Outputs of this module are hydrogen quantities produced onsite (low-emissions or not), electrolyser capacity and related investment requirements, and energy input and related $CO_2$ emissions emitted as well as captured and stored.

### *3.2.3 Non-energy-intensive industries*

Activity modelling for the non-energy-intensive sub-sectors follows a different approach to the energy-intensive sectors. These sub-sectors produce a large range of final products without a clear common intermediate in many cases. This contrasts with the energy-intensive sub-sectors, which have a large range of final products but a clear common intermediate product for which production in physical terms can be projected (e.g. crude steel in the iron and steel sector). Therefore, macroeconomic indicators (e.g. industrial value added) are used as the activity drivers for non-energy-intensive sub-sectors, rather than physical production. Using historical relationships between macroeconomic indicators and industrial energy demand, together with demand signals from the other end-use models (e.g. vehicle sales from the transport model for the transport equipment sector; clean technology manufacturing mostly for the machinery sector; critical mineral and other ore demand for the mining sector) and material efficiency considerations (based on the results of the energy-intensive sub-sector analyses) where relevant, the model projects energy service demand across the following categories:

- Heat delivered at five temperature bands (0-60 °C, 60-100 °C, 100-200 °C, 200-400 °C and above 400 °C);
- Mechanical work to be delivered by motors;
- Other energy services in aggregate (cooling, lighting, etc.).

These energy service demands form the final activity drivers for the non-energy-intensive industry sub-sector models.

A range of technologies are characterised for meeting each category of activity demand, including a range of heating technologies using different fuels (fossil fuels, solar thermal, geothermal, electric heating, heat pumps, hydrogen, bioenergy), thermal energy storage, and a range of motor options (differing in efficiencies of the motor-driven system, efficiencies of the motor itself, variable speed drive option). The shares of energy service

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demand met by each of these technologies are modelled using a Weibull function. This function is informed by each technology's levelised cost (including fuel price evolution and the impact of any $CO_2$ prices), constraints on fuel availability (e.g. bioenergy resources), technology readiness, limits on potential (e.g. industrial heat pump penetration in medium- and high-temperature heat bands) and any $CO_2$ emissions constraints of the scenario.

The shares of fuels (and associated emissions) used to meet the remaining energy service demand of multifuel processes or processes that are not covered by the bottom-up technology modelling across the non-energy-intensive sectors (and residual portions of the energy-intensive sectors not covered in the energy-intensive sub-sector models) are modelled by fuel using a Weibull function. This function is informed by the evolution of fuel prices (including the impact of any $CO_2$ prices). Any $CO_2$ constraints specified by the scenario are also respected.

### *3.2.4 Industry sector investments*

The boundaries for investment reporting include capital expenditure (CAPEX), and engineering, procurement and construction costs. For material efficiency, investments are based on data on $CO_2$ abatement costs for material efficiency strategies, converted into costs for material savings. Fixed operating and maintenance expenditures (OPEX) are not included under reported investments, though they are considered in the economic characterisation of technologies in the model. Energy system investments usually refer to the additional investment required, compared to the prevailing conventional technology, to switch to another technology (e.g. from a boiler to a heat pump, additional investments for a CCUS unit) or increase the energy efficiency (through a detailed efficiency cost curve for each sub-sector to reach best available technologies). The total investments in core industrial equipment are also accounted for but not reported within the boundary of energy system investments (see Section 10.2).

### *3.2.5 Input data*

Input data to the model come from a wide variety of sources. Sources for historical production and consumption used in the activity modelling include the World Steel Association (worldsteel), the International Fertilizer Association, the United States Geological Survey, the International Aluminium Institute and a number of proprietary sources. Data on the energy intensities of processes come from a variety of industry sources (e.g. the Getting the Numbers Right publication overseen by the Global Cement and Concrete Association), academic literature and industry contacts. CAPEX and OPEX similarly come from a combination of industry and academic sources.

Population, economic indicators (e.g. value added by industry), fuel costs – i.e. end-use energy prices – and $CO_2$ prices are provided by the main GEC Model (see Section 2). Other key inputs from the GEC modelling framework and associated work streams include the hydrogen and CCUS projects databases and the technology readiness assessments that form part of the Clean Energy Technology Guide and the Clean Energy Demonstration Projects Database. Techno-economic parameters are periodically reviewed, both as a component of the aforementioned work streams and while preparing "deep-dive" analyses on specific sector or technology areas (e.g. the IEA's Iron and Steel Technology Roadmap, the Ammonia Technology Roadmap, The Future of Petrochemicals).

## 3.3 Transport

The GEC transport model combines the strengths of both the former World Energy Model (WEM) and the Mobility Model (MoMo), and it consists of dedicated sectoral models for road transport, aviation, shipping and rail.

### *3.3.1 The historical database*

One key foundation for transport modelling work is the road transport database, which is updated annually based primarily on publicly available data on road vehicle sales, stocks and activity. The road database further benefits

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from data and analytical work for the Electric Vehicles Initiative (IEA, 2025b). Similar historical databases form the basis for modelling rail, international shipping and aviation.

Each region is characterised on the basis of information that includes – for each road transport mode – vehicle sales, mileage and fuel economy by vintage, as well as the overall vehicle stock and load factors.

The database allows linking historical data on several interconnected variables, trying to ensure internal consistency across indicators, according to the ASIF framework, in which ***A***ctivity, ***S***tructure and ***I***ntensity determine estimates of ***Fuel use:***

$$F = \sum_i F_i = A \sum_i \left(\frac{A_i}{A}\right)\left(\frac{F_i}{A_i}\right) = A \sum_i S_i I_i = F$$

| | |
|---|---|
| $F$ | total ***F***uel use |
| $F_i$ | fuel used by vehicles with a given set of characteristics (***i***) (e.g. segments by service, mode, vehicle and powertrain) |
| $A$ | vehicle ***A***ctivity (expressed in vehicle-kilometres [*vkm*]) |
| $A_i/A = S_i$ | *sectoral* ***S***tructure (same disaggregation level) |
| $F_i/A_i = I_i$ | Energy ***I***ntensity, i.e. average fuel consumption per *vkm* (same disaggregation level) |

The parameters monitored include sales or new registrations of vehicles, second-hand imports, survival ages, stock, mileages, vehicle activity (vehicle-kilometres [vkm]), load and occupancy rates, passenger and freight activity (passenger-kilometres and tonne-kilometres), fuel economies and energy use (based on the IEA data on energy demand by country).

The following parameters are collected and calibrated or validated against the IEA energy balances annually:

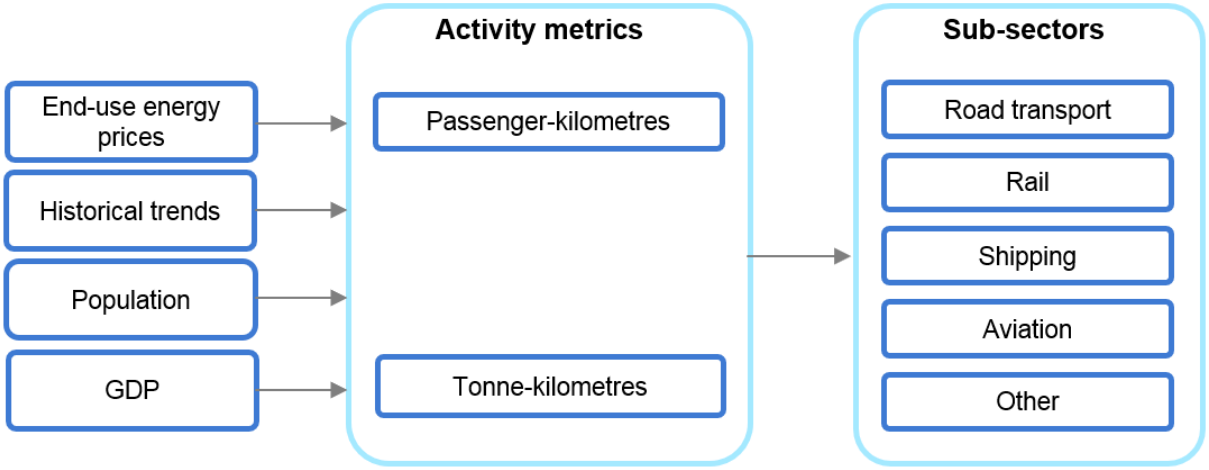
- Sales or new vehicle registration data are taken from publicly available data sources (e.g. the European Automobile Manufacturers' Association [ACEA], US Bureau of Transportation Statistics).
- Fuel economy data for passenger light-duty vehicles are based on aggregated data from a proprietary database of selected countries and government-published datasets (S&P Global Mobility, 2024; EEA, 2025; MIIT, 2024; EPA, 2024a; KEA, 2025) plus conversions across regional vehicle test cycles to the Worldwide Harmonised Light Vehicles Test Cycle (WLTC) (based on (ICCT, 2014; ICCT, 2021a; EEA, 2025; EPA, 2024a)). The gap between type-approval WLTC fuel economy and real-world equivalent values is derived from real-world $CO_2$ emission data collections (European Commission, 2024a; EPA, 2024b; ICCT, 2021b; ICCT, 2023; ICCT, 2024).
- Fuel economy data for buses, trucks and two/three-wheelers are taken from various academic, government and industry reports or technical calculations.
- Stocks are based on our estimates of how long different vehicle types are kept in the fleet (i.e. scrappage functions), and when reliable external estimates are available (as is the case, for instance, in Europe and the United States). Stocks are calibrated to national statistics or industry reports (e.g. ACEA, US Bureau of Transportation Statistics). In countries where academic or industry studies exist on the age distribution of the on-road fleet, scrappage functions are compared or calibrated with these.
- Occupancy (average number of people per vehicle) and load factors (average cargo weight per vehicle) are generally informed by official statistics (e.g. Eurostat), academic reports or surveys, or are developed by analogy or regression-based estimates when no data are available.
- Average mileage (i.e. annual kilometres driven) estimates are similarly taken from, compared or calibrated to official data and literature. Mileages are then adjusted across all vehicle categories (e.g. two/three-wheelers, cars, buses, light commercial vehicles, medium freight and heavy freight trucks) and across all fuel and powertrain types (e.g. gasoline, diesel, conventional hybrid, plug-in hybrid, battery and fuel cell electric) to match the country or regional time series of road gasoline, diesel, electricity and natural gas consumption as reported in the IEA energy balances.

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### 3.3.2 The transport module

The transport module consists of several sub-models covering road, aviation, rail and navigation transport modes (Figure 3.5) and incorporates a detailed bottom-up approach in all model regions.

**Figure 3.5 ▷ Structure of the transport demand module**




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Notes: GDP = gross domestic product. Other includes pipeline and non-specified transport.

Regional transport activity, such as passenger-kilometres and tonne-kilometres, widely referred to as service demand, is estimated econometrically for each mode of transport as a function of population, GDP, urbanisation rates and end-user prices. Transport useful energy demand is defined as the tractive energy needed to meet this service demand. The methodology for useful energy demand modelling in transport is described in Section 3.1.5.

Elasticity of transport demand to fuel cost is modelled for all modes except rail and navigation. The elasticity variable accounts for the "rebound" effect of increased transport demand that follows improved fuel efficiency. Energy intensity is projected by transport mode, taking into account changes in energy efficiency and fuel prices.

Because shipping and aviation activity operate across regions, models for these modes require a global approach. In the shipping module, we rely on activity needs derived from IEA trade projections. Aviation activity between city pairs is estimated with a gravity-type model, as implemented in the Aviation Integrated Model (AIM) (Air Transport Systems Lab, 2026).

Additionally, analysis of the composition of road vehicles and ships is combined with sales projections to produce estimates of demand for materials such as steel and aluminium over time. These projections inform the IEA's ongoing work on material demand and subsequent heavy industry activity.

#### *Road transport*

The road freight activity module estimates the price elasticity of diesel demand using historical data. Future trends take into account changes in GDP and end-user fuel prices over time. The road passenger vehicles module uses vehicle ownership curves, based on the Gompertz function, to project the future evolution of ownership ratios.

Road transport energy demand is broken down into passenger light-duty vehicles (PLDVs), light commercial vehicles (LCVs), buses, medium-freight trucks, heavy-freight trucks and two/three-wheelers. The model allows fuel substitution and alternative powertrains across all road vehicle types.

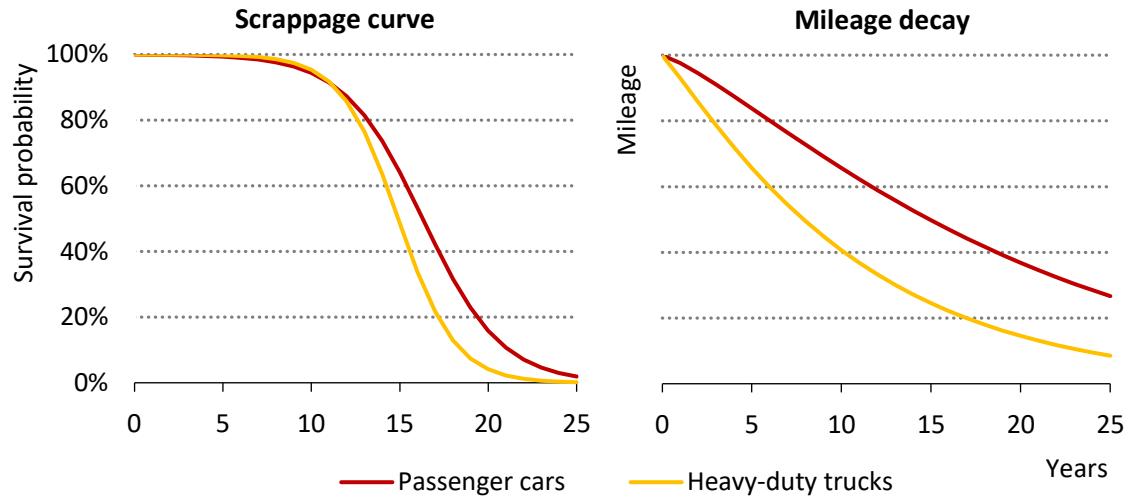
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As the largest share of energy demand in transport comes from oil use for road transport, the GEC Model contains technology-detailed sub-models of the total vehicle stock. The stock projection model is based on an S-shaped Gompertz function, proposed in Dargay, Gately, and Sommer (2007). This model gives the vehicle ownership based on income (derived from GDP assumptions) and two variables: the saturation level (assumed to be the maximum vehicle ownership of a country or 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). These three parameters (y, a and b) are based on the historical correlation between GDP per capita and vehicle ownership, additionally taking into account several country- or region-specific factors such as population density, urbanisation and infrastructure development. Reference groups of template S-curves are derived from observed historical private vehicle ownership and income data, as well as from available studies. Using the equation above, changes in passenger car and two/three-wheeler ownership over time are modelled, incorporating the curve-fitting approach on the reference S-curves for both vehicle types. Bus ownership projections also take into account competition with non-high-speed passenger rail, with Gompertz curves fitted based on correlation with GDP per capita and the share of public transport in the total road and rail passenger activity. Having already modelled private vehicle (cars and two/three-wheelers) and rail activities, we can derive bus activity projections and later include additional activity shift from PLDVs to buses based on fuel price elasticity projections. Thereafter, we project the evolution of ownership ratios across all passenger vehicle types. Based on our population assumption, stock projections are derived accordingly. Projected vehicle stocks and the corresponding vehicle sales, calculated from new registrations required to reach projected stock levels, taking fleet scrappage curves into account. These sales projections are benchmarked against other studies of annual vehicle sales trends, particularly in the short term.

**Figure 3.6 ▷ Illustration of scrappage curve and mileage decay by vehicle type**




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To improve the modelling of the vehicle fleet's stock evolution, a dynamic scrappage function has been developed in which dedicated scrappage curves are estimated by region based on a correlation of average lifetime with economic growth. The dynamic scrappage function allows us to evaluate policy measures such as those for the early retirement of vehicles (Figure 3.6). To take into account that older vehicles are used less

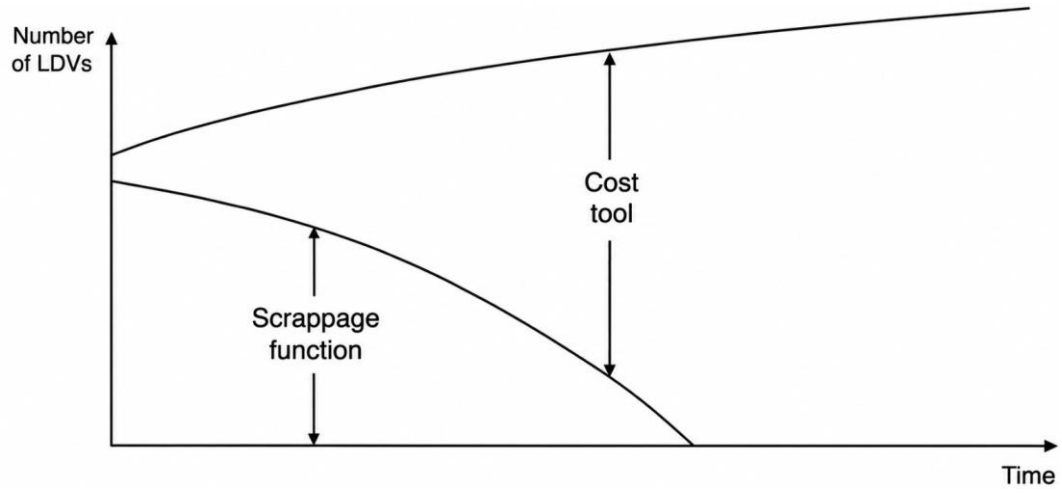
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frequently, an extensive literature review has been carried out to identify mileage curves per vehicle type. This enables a more granular assessment of how each vehicle type per vintage (purchase year) is contributing to total road activity.

The road transport model also includes a dedicated used-car trade module to project bilateral flows of used passenger cars across GEC Model regions. Used vehicle import demand is projected based on historical import shares, car purchase cost and price depreciation, average imported vehicle age and the evolution of GDP per capita. Potential exports are derived from projected vehicle retirements and historical export shares from the road transport model. Historical bilateral trade patterns provide the initial distribution of flows between importing and exporting regions. These flows are then balanced against importer demand and exporter supply potential using iterative proportional fitting, while accounting for policy constraints, including limits on the age of imported vehicles and used ICE car import bans. The model distinguishes vehicles by powertrain and, where import age restrictions are applied, uses vehicle retirements by vintage and powertrain to determine the supply eligible for each importing region. This allows changes in the composition of vehicle fleets in exporting regions, including increasing electrification, to propagate through international used-car trade and affect the composition of car fleets in importing regions. This also affects the improvements in fuel economy resulting from used-car trade volumes.

The analysis of PLDVs 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 PLDV sales as depicted in Figure 3.7 and determines the share of each individual technology in new PLDVs sold in any given year. The composition of used cars is determined by the used-car module. Together, the two modules determine the overall composition of the car fleet in each region.

**Figure 3.7 ▷ The role of the passenger light-duty vehicle cost model**




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Note: LDVs = light-duty vehicles.

The purpose of the cost tool is to guide the analysis of technology choices using their cost competitiveness as one important criterion. The tool uses a logit function for estimating future drivetrain choices in PLDVs.[2] The share of each PLDV type *j* allocated to the PLDV market is given by:

[2] 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, they use the cost-competitiveness of technology options as an indicator for the pace of growth.

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

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; and
- $b_j$ 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 fuels, comprising the following technology options:

- conventional ICE vehicles (spark and compression ignition)
- hybrid vehicles (spark and compression ignition)
- plug-in hybrid electric vehicles (spark and compression ignition)
- battery electric vehicles
- hydrogen fuel cell vehicles.

The module 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 and fuel cells (Tsiropoulos et al., 2018). The pace of technology cost reductions is then calculated using learning curves at technology-specific learning rates.

The cost analysis builds on a comprehensive and detailed review of technology options for reducing fuel consumption. Cost curve assumptions across all vehicle types are based on work by the Joint Research Centre (JRC) (JRC, 2017; JRC, 2018b; JRC, 2023) and they have been updated with the latest data available. Regional characteristics and economic factors have been taken into account in order to expand cost curve coverage for all GEC Model regions. This analysis not only covers the incremental costs of the technology but also assesses the overall evolution of the vehicle market in monetary terms, which feeds into the investment module.

Projected sales of alternative powertrains are benchmarked against automakers' announced targets each year. This analysis allows for an assessment of whether vehicle manufacturers' commitments to launch new electrified vehicle models are falling behind the necessary EV rollout for meeting fuel economy targets and zero-emission vehicle mandates, as reflected in IEA scenarios. Vehicle manufacturers and national and state jurisdictions with ICE phase-out commitments for a certain year are also part of this process.

Future battery demand from EVs is derived from projected EV volumes based on the approach described above, along with projections about average battery size and cell cathode chemistry. These projections are linked to historical EV battery sizes by country and bottom-up analyses of battery costs and critical mineral requirements. The projected share of extended-range electric vehicles is based on their cost competitiveness and performance relative to conventional PHEVs. Additionally, the PHEV energy consumption module has been improved by using our latest PHEV driving range projections and utility factor equations in force in all regions known to have a PHEV-specific regulatory framework (e.g. the European Union, Japan and the United States). In other regions, the utility factor equation set to enter into force in 2027 in the European Union is considered (European Commission, 2023).

Hydrogen fuel cell electric vehicle projections take into account the recent car market developments, policy announcements and the key outcomes as described in the IEA's *Global Hydrogen Review 2026* (IEA, 2026d).

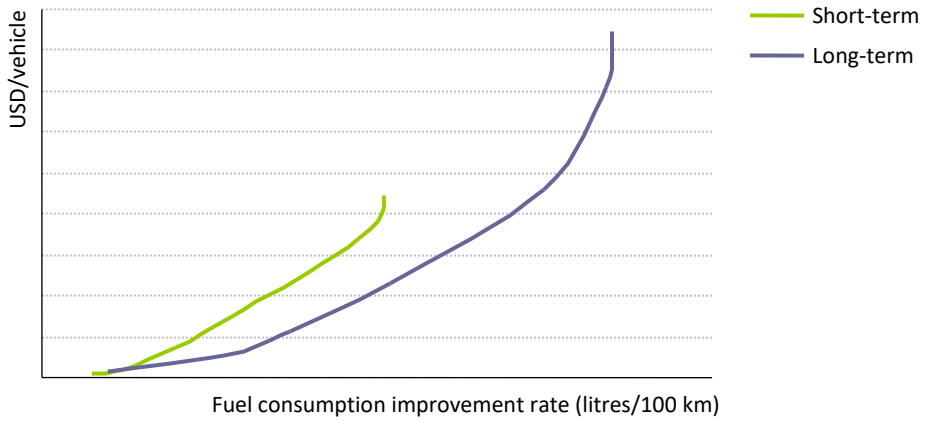
Road freight transport vehicles can be broadly classified into LCVs (< 3.5 t), medium-freight trucks (3.5 t to 15 t) and heavy-freight trucks (>15 t). For the latter two categories, the GEC Model comprises two detailed sub-models

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to guide the development of average fuel economy improvements on the one hand, and technology choices on the other hand. For fuel economy improvements, the model endogenises the decision to invest in energy efficiency by taking the view of rational 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 the JRC, the model calculates the undiscounted payback period of an investment into more fuel-efficient medium trucks and heavy trucks. The model then allows for investments where the calculated payback period is shorter than a maximum acceptable payback period that is required by fleet operators (generally assumed to be between one and three years, depending on the region). The problem is solved iteratively as the model seeks to deploy the next efficiency step on the efficiency cost curve as determined by literature, but it may use efficiency improvement levels in between individual steps (Figure 3.8).

As a second step, the model simulates the cost effectiveness of a conventional ICE vehicle against competing alternative options. The simulation is guided by a Weibull function. Alternative powertrains for medium- and heavy-freight trucks have been implemented in the GEC Model: fuel cell, battery electric and plug-in hybrid electric.

**Figure 3.8 ▷ Illustration of an efficiency cost curve for road freight**




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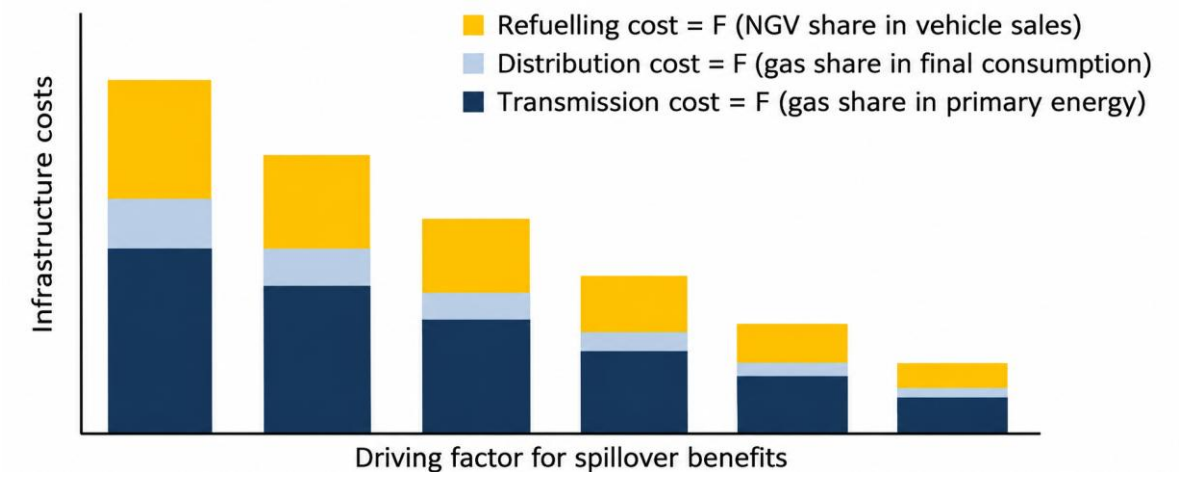
The road freight module uses regional analysis to assess freight activity, taking into account the geographical and economic characteristics of the countries under examination. This module provides projections by factoring in economic indicators and the dynamics of fuel prices. It provides valuable insights into both the future trajectory of freight activity and the evolving load factors for different truck size categories.

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 test cycle) and average emission levels (in grammes of $CO_2$ per kilometre) over the projection period. The model takes into account second-hand market trends in fuel economy evolution, mainly for passenger cars, and assesses the impact of policies in countries importing vehicles from regions with ambitious fuel economy goals. It further determines incremental investment costs relative to other scenarios and calculates implicit $CO_2$ prices that guide optimal allocation of abatement in transport.

To assess the problems created by chicken-and-egg-type situations in the deployment of those alternative fuels in transport that require a dedicated refuelling infrastructure, and to better reflect potential spillover effects of the use of such alternative fuels in other sectors of the energy system, the GEC Model has dedicated sub-models for covering refuelling infrastructure (Figure 3.9). In principle, the modules seek to quantify the costs and benefits of increased infrastructure availability for transmission and distribution of these alternative fuels.

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**Figure 3.9 ▷ Refuelling infrastructure cost curve** (illustrative)




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Note: NGV = natural gas vehicle.

For electric vehicles, availability of a robust transmission and distribution grid is less of an issue, especially in advanced economies, thanks to the already widespread use of electricity in different end-use sectors (notably buildings). However, the availability of electric recharging infrastructure is one of the main 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. In our modules, we estimate future charging infrastructure requirements based on the projected EV fleet under the IEA scenarios.

EV supply equipment (EVSE or EV charger) stock is also projected by vehicle category via a dedicated EVSE module. For light-duty vehicles, the number of public chargers is based on historical trends of EVSE/EV stock and the share of slow and fast chargers, where reliable regional data are available. Over time, the charger mix evolves towards higher-power technologies through new installations and replacements at the end of their assumed service life. The pace of the deployment of private and public charging infrastructure is informed by data on the access to home charging and the current level of publicly available charging ports and stations. With an increasing share of population living in urban areas, access to home charging decreases in future years. In general, the public EVSE-to-EV ratio is projected such that as the EV stock share increases, the required kilowatts (kW) of public charging capacity per EV decreases to reflect that the system becomes better optimised as the market matures. For buses and trucks, the share of electricity demand met through opportunity or public chargers is projected by segment. The required number of public chargers is then estimated based on an assumed mix of chargers with different charging capacities. Depending on the future evolution of EVSEs, we assume that costs will decline over time in line with learning curves. At the same time, we estimate the investment needs associated with infrastructure deployment, accounting for both the installation of new equipment and the replacement of retired infrastructure.

Hydrogen fuel consumption is used to estimate the number of hydrogen refuelling stations (HRS) needed to meet future demand. Station capacities are modelled to grow over time, with different size limits set based on the target vehicles being served. For example, HRS for trucks have higher maximum capacities than stations to serve the light-duty vehicles. Of course, some stations will have dual-pressure dispensing and serve different vehicle markets. However, the modelling also differentiates utilisation rates by target vehicle category: stations for fleets of buses and trucks are expected to have higher average utilisation rates than those for light-duty vehicles. Thus, the stock of HRS required to serve fuel cell electric vehicles (FCEVs) is:

$$HRS\ Stock\ = \sum \frac{F_i}{C_i \times U_i}$$

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Where:

- $i$ represents the vehicle category
- $F_i$ represents the hydrogen fuel demand (kg $H_2$/year) of vehicle category $i$
- $C_i$ represents the average nameplate capacity (kg $H_2$/year) of HRS serving primarily category $i$
- $U_i$ represents the average utilisation rate (%) of HRS serving primarily category i.

### *Rail*

The rail module is built on a historical database that covers five different rail types and four fuels across more than 130 countries. Key parameters include energy intensity, activity, mileage, stock and load/occupancy factor, as well as track length and utilisation. Three different scrappage curves are used to derive historical train sales numbers per rail type and fuel.

In the database, rail vehicle and passenger/freight activity are calibrated across urban (metro and light rail) and non-urban (conventional and high-speed passenger rail, and freight rail), for diesel, electricity and coal, to match the energy balances at the country level.

Rail modelling builds upon databases of urban rail activity (metro and light rail) from the International Association of Public Transport and the Institute for Transportation and Development Policy, including databases of urban rail infrastructure. It further builds upon data from the International Union of Railways (UIC) and the JRC on intercity (conventional), high-speed and freight rail activity and stock. Infrastructure projections for all rail types draw on data from Global Mass Transit and the UIC. Rail activity per type is calibrated to the data collected from government statistics, the World Bank, the United Nations Economic Commission for Europe, and the UIC. Efficiency benchmarks by rail type are based on the latest JRC data. Electrification and hydrogen penetration rates in conventional passenger and freight rail are informed by historical trends, current and announced rail projects and targets, as well as regulatory, fiscal, investment and climate policies that vary by scenario.

Energy intensity, occupancy/load factor, mileage and track utilisation are projected with consideration of GDP/capita and the historical performance, and they vary by scenario. Activity projections per rail type are based on a comprehensive elasticity model using historical activity, as well as GDP, population and infrastructure projections. The impact of behavioural change in the rail module is differentiated between HSR and non-HSR, also varying by scenario. The impact of behavioural changes in the rail module is differentiated between HSR and non-HSR, also varying by scenario. For HSR, activity growth resulting from behaviour change considers aviation-to-rail shifting informed by countries' NDCs. For non-HSR, activity growth due to behavioural change is based on historical track utilisation and rail passenger activity per capita data, as well as the role of rail in the NDCs.

### *Aviation*

Aviation modelling builds upon the open-source Aviation Integrated Model (AIM) (Air Transport Systems Lab, 2026), developed and maintained by researchers at University College London. Key features of AIM preserved in IEA modelling include:

- High-resolution aviation system modelling, with over 1 000 airports, nine aircraft size classes and extensive options and combinations of aircraft technologies (new and retrofit) and fuels.
- Operational and technical potential for energy intensity improvements based on detailed origin-destination modelling of aircraft and airport operations and airframe-propulsion systems, with stock and techno-economic modelling, in the framework of iterative cost minimisation.
- Regional and airport-resolution long-term price and GDP demand elasticities aligned with International Air Transport Association (IATA) (2007) and other authoritative studies, enabling credible and high-resolution activity projections for both passenger and freight.

Projections integrate the main features of detailed iterative cost minimisation modelling using AIM with "top-down" projections of fuel consumption by other aviation activities (private, military). For every vintage of model results, the main inputs to AIM are updated with the latest in-house analysis:

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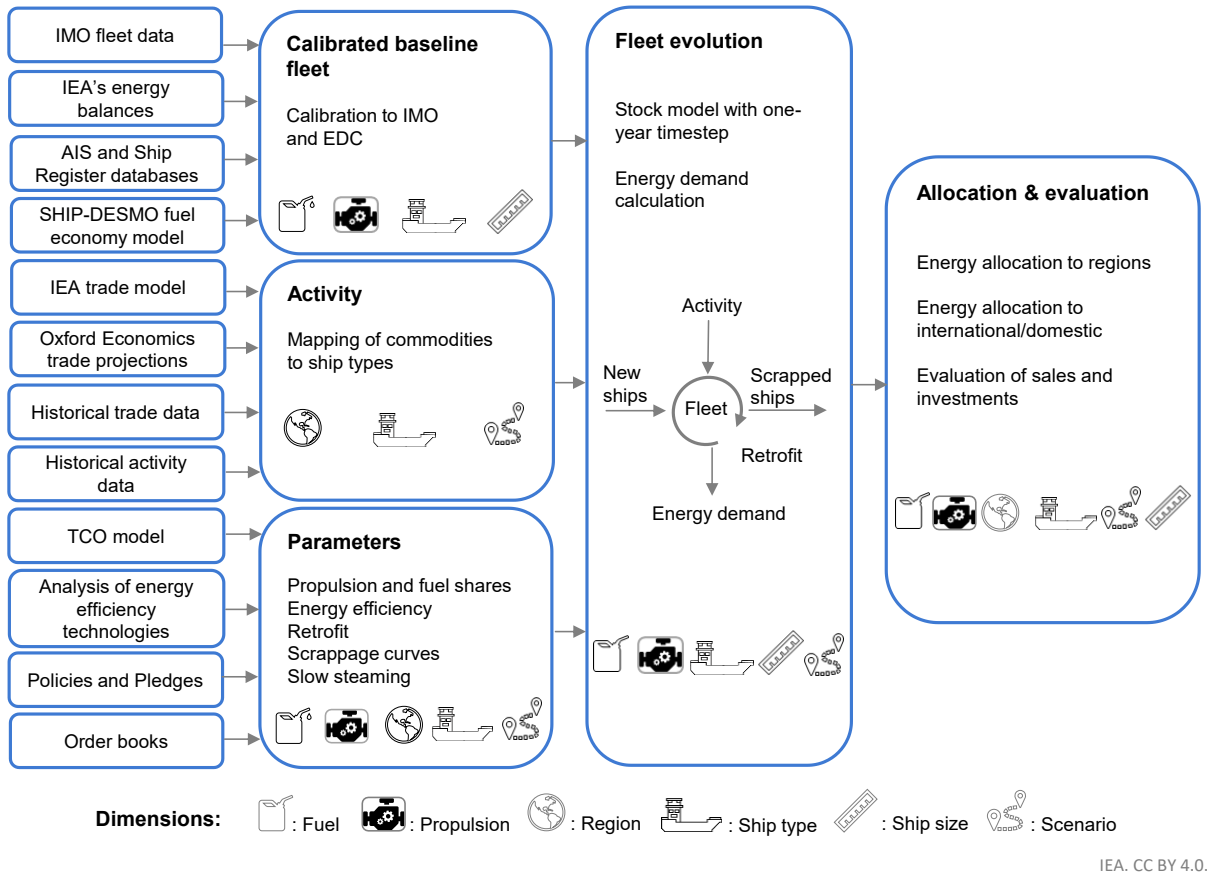
- country-level GDP and population projections
- fuel price projections
- policies, such as fuel share mandates/targets and carbon pricing
- assumptions about future aircraft technology.

AIM modelling results are calibrated to the latest available activity numbers from authoritative sources, such as International Civil Aviation Organization (ICAO) (2010-2024), IATA (2026), and Official Aviation Guide (OAG) (2026), as well as to the IEA's energy balances. Scenario projections are iteratively refined to align with fuel production capacity projections and to reflect policies and pledges, including demand-side options (see the section on behavioural change analysis below).

### *Shipping*

The methodology of the bottom-up model for shipping energy demand is illustrated in Figure 3.10. Activity projections, a calibrated baseline fleet and scenario-specific parameters are inputs into a dynamic stock model that calculates the evolution and the energy demand of the global shipping fleet by ship type, propulsion and fuel. This energy demand is subsequently allocated across regions and to either the international or the domestic shipping sectors.

**Figure 3.10 ▷ Shipping model methodology**




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Note: AIS: automatic identification system; EDC: energy data centre; IMO: International Maritime Organization; TCO: total cost of ownership.

The characteristics of the baseline shipping fleet, including distributions of ship type, size and age, are sourced from the Ship Register, accessed via the UN global platform (United Nations, 2025). The model explicitly includes the following ship types: container ships, bulk carriers, oil tankers, general cargo, liquefied gas tankers and

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chemical tankers. These ship types accounted for 75% of global shipping GHG emissions in 2018 (IMO, 2025), while the remainder of the fleet is categorised as “other ships”. Automatic Identification System (AIS) data, also obtained through the UN global platform (United Nations, 2025), is used to derive distributions of speed, average distance travelled, days spent at sea and load factors, and shares of international versus domestic voyages per ship type and size. Energy consumption (energy intensity) of ships in the existing stock is calculated with the SHIP-DESMO model (Technical University of Denmark, 2016). The resulting energy demand is then calibrated to align with International Maritime Organization (IMO) energy consumption data by ship type (IMO, 2025) and the IEA’s Energy Balances in the historical years, separately for the international and domestic portions. In IEA energy balances, domestic navigation energy demand includes fuels delivered to vessels of all flags not engaged in international navigation. This excludes fuel used for ocean, coastal and inland fishing, and military consumption. International marine bunkers, on the other hand, covers fuel quantities delivered to ships of all flags engaged in international navigation, and it excludes fishing vessels and military forces. The domestic/international split is determined by port of departure and port of arrival, and not by the flag or nationality of the ship (IEA, 2025c).

Activity projections are derived from a bottom-up tool that uses a variety of data sources. For historical years, trade data from Centre d'Études Prospectives et d'Informations Internationales's (CEPII) Base pour l'Analyse du Commerce International (BACI) (CEPII, 2026) are used. Historical world total shipping activity is aligned with United Nations Conference on Trade and Development data (UNCTAD, 2025). For activity projections, IEA internal trade projections for energy commodities (oil, gas, coal, hydrogen and alternative fuels) and trade flows for key materials and clean energy technologies from the IEA’s MaT model (see Energy Technology Perspectives 2024 (IEA, 2024a) for more information) are used to compound overall international shipping activity so that internal consistency by scenario is ensured. For commodities outside the scope of IEA trade modelling (accounting for about one-third of traded mass in 2025 projections), Oxford Economics (Oxford Economics, 2024) forecasts are used. Trade flows of commodities are allocated to ship types, determining the activity for all explicitly modelled ships. Other ships are treated with a simplified approach: activity is estimated through econometric scaling.

Input parameters to the model are informed by several sources, including a total cost of ownership (TCO) model, an analysis of existing energy efficiency technologies and their impact on different ship types, order books for new ships, and policy measures and pledges. Some policies directly influence the inputs (e.g. allowed emission intensity for the fuels), and others concern the outputs (e.g. targets on total sectoral emissions) and need to be translated into suitable inputs. The TCO model identifies the most cost-effective propulsion and fuel options for various ship types and sizes.

A dynamic stock model calculates the annual evolution of the global shipping fleet, in which the necessary stock of each ship type is derived based on the shipping activity, average distance travelled and size distribution. Scrappage curves determine ship retirements based on the age distribution of the fleet, and new ships are added to ensure activity projections can be met. Eligible ships, determined based on ship type, ship size and age criteria, are either upgraded with various energy efficiency measures or retrofitted with alternative propulsion systems. The model then calculates energy demand based on energy consumption drivers (size, speed, load factor, distance travelled) and ship efficiencies. For non-explicitly modelled ships (“other ships”), energy efficiency and fuel share inputs are directly applied to calculate energy use by fuel type.

The global energy demand by ship and propulsion type is then allocated across regions and sectors (international or domestic). Regional allocation is based on historical and extrapolated energy demand and thus reflects where bunkering occurs.

### *Behavioural change analysis*

Several analyses regarding behavioural change in transport have been carried out:

- Ex-post analysis of the impact of behavioural change on the aviation sector has been developed. Historical data (OAG, AIM from UCL) have been used to disaggregate aviation activity per person and distance. Changes in occupancy factors have been assumed to assess the impact of behavioural change on oil demand.

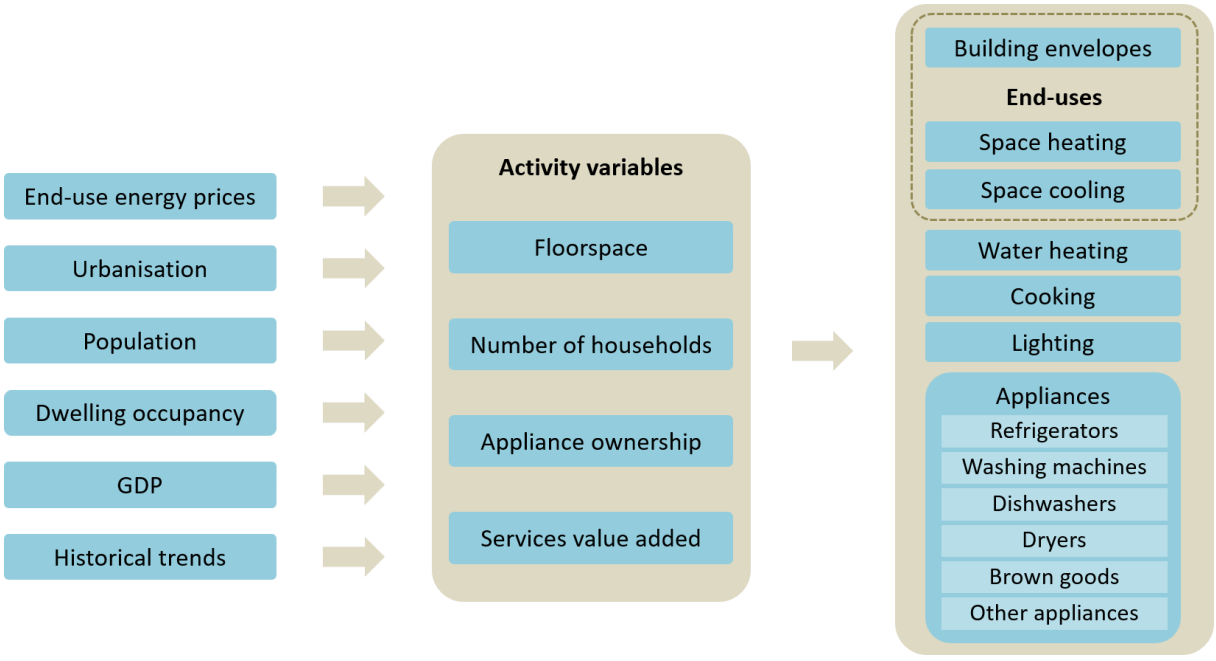
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- Both commercial (IHS Markit, Jato Dynamics, Marklines) and in-house (Global Fuel Economy Initiative, historical road database) datasets have been used to perform in-depth analysis by country on the rise of sport utility vehicles (SUVs). Based on an analysis of historical trends, a moderate growth of SUVs is projected in the STEPS on a global scale.
- The car market is analysed using multiple sources (Marklines, EV Volumes, etc.) to estimate the future evolution of car sales. Based on a stock model, a change in car sales volume due to both new purchases and replacements is estimated. Econometric functions have been applied to project the future trend.
- During the Covid-19 pandemic, data showed a shift from public transport to private vehicles due to health concerns. Publicly available reports, including surveys by Ipsos, were used to estimate the mobility needs that were covered by bicycles or private cars. Assumptions differ by GEC Model region, depending on the accessibility of bikes. The impact of this modal shift on oil demand was estimated.
- With regard to the impact of working from home, a literature review has been carried out on the average commuting distance by transport mode for key GEC Model regions. These data have been extrapolated to all regions. Assuming the maximum potential for the workforce to work from home (i.e. 20% by 2030), the impact on oil demand was assessed.

## 3.4 Buildings

The buildings sector module of the GEC Model is subdivided into the residential and services sectors, both of which have similar structures (Figure 3.11). Data centres and water desalination, which both fall within the services sector, are modelled independently. Population, GDP, climate and dwelling occupancy inform the activity variables, which include floorspace, appliance ownership, number of households (for the residential sector) and value added (for the services sector).

**Figure 3.11 ▷ Structure of the buildings demand module**




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Note: GDP = gross domestic product.

Within the residential and services sectors, energy demand is subdivided into six standard end-uses in buildings, namely space heating, water heating, appliances, lighting, cooking and space cooling. Appliances are divided into

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four main categories: refrigeration (refrigerators and freezers), cleaning (washing machines, drying machines and dishwashers), brown goods (televisions and computers) and other appliances. Space cooling comprises small and large size air conditioners, ground-source heat pumps, district cooling, fans and other cooling technologies that are alternatives to vapour compression. All listed end-uses within each sector are modelled individually, and final energy consumption is projected from the base year for each end-use in three steps.

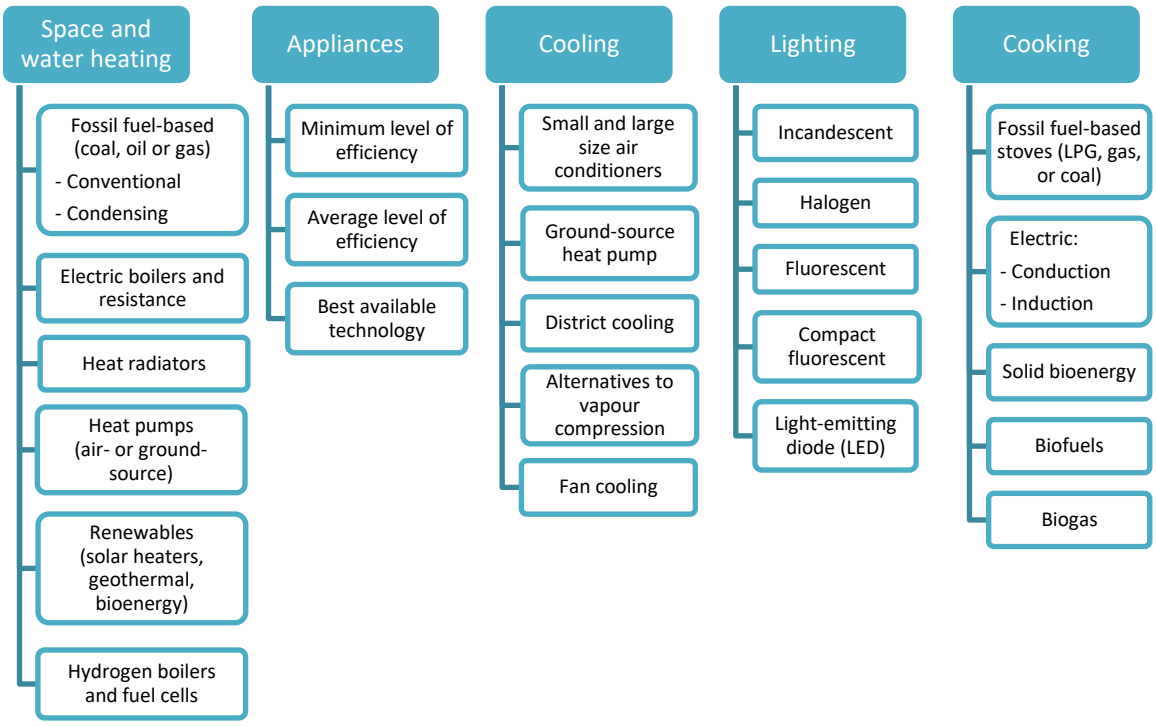
**The first step is calculating the demand for an energy service, i.e. the useful energy demand, based on activity variables.** The basic concept for this step is:

$$End\ use\ useful\ energy\ demand = Activity\ variable \times intensity$$

The methodology for useful energy demand modelling is described in Section 3.1.3. The buildings module estimates useful energy demand by combining activity levels with end-use energy intensities, calibrated using historical energy consumption, equipment stocks and efficiencies. Projections account for changes in activity, fuel prices and incomes, with heating and cooling additionally adjusted for weather variability, climate change and energy performance of building envelopes. Total heating and cooling demand is aggregated across building vintages and performance categories, reflecting scenario-specific assumptions about new construction, compliance with building energy codes and retrofits.

**The second step is choosing the technologies to supply the end-use useful energy demand.** For each end-use, there is a detailed set of technologies available in the model (Figure 3.12). Most of the technology options are modelled in tiers, representing varying levels of energy efficiency and associated investment costs. Additionally, it is possible to switch fuels and technologies, whereby, for example, 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 cookstoves and household heating equipment.

**Figure 3.12 ▷ Major categories of technologies by end-use sub-sector in buildings**




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Note: LPG = liquefied petroleum and gas.

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Over the projection horizon, the technology choice is based on technologies' relative costs, their efficiencies and any relevant constraints in the region considered. Technology shares are allocated by a Weibull function that accounts for each technology's costs per unit of useful demand supplied, which include investment costs, operation and maintenance costs and fuel costs. For example, the relative economic competitiveness of a heat pump versus a gas boiler for space heating differs depending on the building's useful demand for heating, which impacts the importance of investment costs relative to operational costs. The model routine allocates different technologies to satisfy the additional useful demand each year over the model horizon. This allocation is subject to upper and lower boundaries, reflecting real-world constraints such as technology availability, policies and market barriers.

To assess and update equipment and appliance efficiency, and related costs, many companies, experts and research institutions at the national and international levels, including IEA Technology Collaboration Programmes, are regularly contacted. The assessment was also supported by an initial extensive literature review to catalogue technologies that are now used in different parts of the world and to judge their probable evolution.

**The third step is calculating total final energy consumption in the residential and services sectors based on the efficiencies of existing and new building equipment.** Efficiency represents the amount of useful energy provided per unit of energy consumed and thus the technical performance of the equipment or appliances. Final energy consumption in the buildings sector is the sum 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 model horizon by the technology allocation routine.

$$Final\ energy\ consumption = \frac{1}{Efficiency} \times End\ use\ useful\ energy\ demand$$

The impact of behavioural change is integrated at this point, with both the energy use and useful energy demand per technology adjusted to reflect scenario assumptions on the breadth and depth of behavioural change in the buildings sector.

Model outputs, in terms of energy demand by technology, the number of technology units deployed and buildings constructed or retrofitted, are all used to calculate investments and energy expenditure. $CO_2$, other GHG emissions and material needs (steel, cement and aluminium) related to the buildings sector are also calculated.

The buildings module is directly linked to the energy access module to account for the growth of electricity access and of alternative fuels or stoves for cooking (see Section 11).

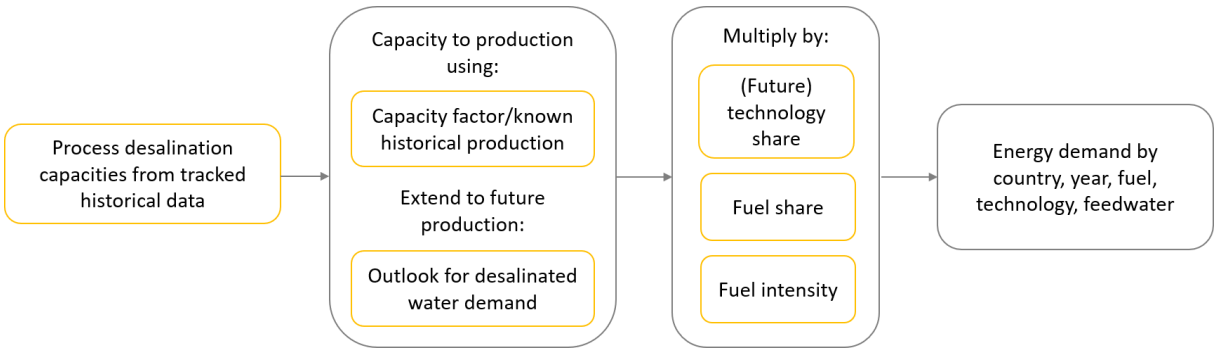
### *Desalination*

Energy consumption for the desalination of water is modelled within the services sector. The starting point of this analysis is a dataset from GWI DesalData (GWI, 2026) tracking desalination plants globally, which includes granular information on location, technology, feedwater, production capacity and online date. Some countries with substantial desalination capacities publish statistics on annual desalination volumes; where available, these are taken into account. Energy consumption values are derived from water production based on the fuel shares and energy intensities of different desalination technologies.

Projections for the future demand for desalinated water are made by considering historical trends, technology development and current policies, and using regional data on the availability of renewable freshwater resources and sectoral water consumption. The scenarios also account for different rates of efficiency improvements and technology uptake (Figure 3.13). The technologies modelled comprise multi-effect distillation, multi-stage flash, other thermal technologies and electric desalination technologies (notably reverse osmosis).

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**Figure 3.13 ▻ Structure of the desalination energy demand model**




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### *Data centres*

Data centre electricity demand is classified under the services sector following the International Standard Industrial Classification of All Economic Activities (ISIC). The modelling of data centre electricity demand relies on a bottom-up approach developed by the Lawrence Berkeley National Laboratory over the past two decades. In this modelling approach, information technology (IT) equipment shipments are the key driver of data centre electricity demand. We analyse three types of IT equipment: servers, storage systems and networking equipment. The last category refers to network equipment hosted within data centre facilities to connect servers and storage devices to the data network. It should not be confused with the data transmission network (for example, 5G network towers), which connects data centres and end-users. The latter falls outside the scope of the modelling of data centre electricity consumption.

The central input to the model is the annual shipments of servers. These come from:

- Omdia (2026a), which provides shipment projections for the period 2016-2030.
- These are triangulated with additional data inputs from Omdia (2026b), SemiAnalysis (2025) and Borderstep Institute (Hintemann, Hinterholtzer, & Konrat, 2024), and additional literature (CBS, 2025; CSO, 2026; DCCEEW, 2025; DRCSC, 2024; Gartner, 2014a; Gartner, 2014b; Gartner, 2014c); (Gartner, 2015a; Gartner, 2015b; Gartner, 2015c; Gartner, 2015d; Gartner, 2016a; Gartner, 2016b; Gartner, 2017a; Gartner, 2017b; Gartner, 2018a; Gartner, 2018b); (Gartner, 2020; Kamiya & Coroamă, 2025; Koomey J. , 2011; Maeil Business, 2024; Malmodin, Lövehagen, Bergmark, & Lundén, 2024; Masanet, Shehabi, Lei, Smith, & Koomey, 2020; National Grid, 2025; Koomey J. , 2011; Shehabi A. , Smith, Masanet, & Koomey, 2018; Singapore, Ministry of Digital Development and Information, 2021); (Wood Mackenzie, 2025)

Based on these datasets and input assumptions, we estimate the installed capacity for each type of IT equipment. These values differ from the maximum designed capacity, as they consider only the installed units of each IT equipment type and do not reflect total rack capacity.

The stock of storage drives is derived from hard disk drive shipment data from Forbes (2021) and the split between hard disk drives and solid-state drives from Shehabi et al. (2024). The stock of network equipment is estimated based on server port density.

The technical characteristics of the IT equipment stock, such as lifetime and power consumption, as well as operational characteristics like idle power ratio and server utilisation rates, are based on estimates from the United States (Shehabi A. , et al., 2024).

Network equipment is assumed to have a 100% utilisation rate. Storage system utilisation rates are considered constant. Idle power assumptions are based on trends observed in the Server Efficiency Rating Tool (SERT) database for conventional servers and estimates from the literature for accelerated servers (SPEC, 2024; Shehabi A. , et al., 2024).

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Utilisation rates are aggregated by data centre type. The equation for the electricity consumption of servers is as follows:

$$E = (P_{max} - P_{idle}) * u + P_{idle}$$

Where:

- $P_{max}$ is the maximum power draw of an operating server (distinct from the maximum rated power, especially for accelerated servers).
- $P_{idle}$ is the power drawn by a server when not processing useful tasks.
- $u$ is the server utilisation rate.

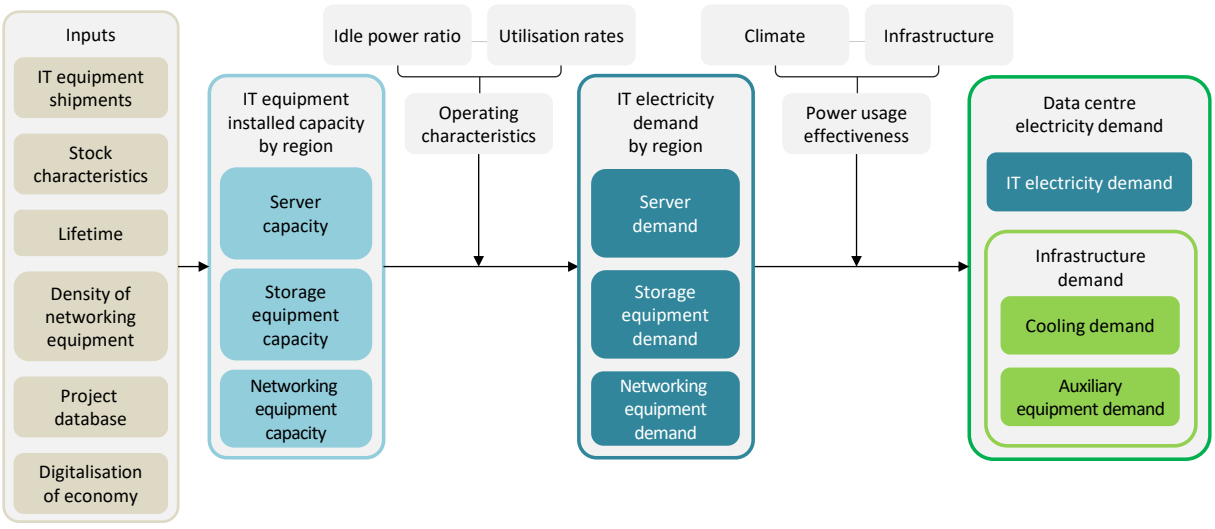
We distinguish three types of data centres, which serve as archetypes in this model: enterprise data centres, colocation and service provider data centres, and hyperscale data centres.

The regional allocation of global installed IT capacities relies on several factors. The primary driver is the regional breakdown from our third-party data provider (IDC, 2024), which is based on market dynamics in each region. To achieve finer regional granularity, we also consider a project database from Omdia (OMDIA, 2026b), the level of digitalisation of economies based on the digital adoption index and the development of the local data centre market, using publicly available data on market revenues (Statista, 2024).

For each region and data centre type, IT electricity demand is multiplied by the corresponding power usage effectiveness (PUE) to obtain the total electricity demand of the infrastructure and hosted IT equipment (Figure 3.14).

PUE primarily accounts for cooling equipment, power supply equipment and lighting. Power supply equipment and lighting are collectively referred to as "auxiliary equipment". PUE estimates are based on regional climate and infrastructure efficiency (Lei & Masanet, 2022). The relative evolution of PUE over time is informed by improvements reported in company-level data (Google, 2025).

**Figure 3.14 ▷ Structure of the data centre electricity demand model**




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Note: IT = information technology.

### *Behavioural change*

Behavioural changes modelled within the buildings module include lower indoor air temperature settings, lower use of air conditioning, use of line-drying, efficient use of lighting and appliances, optimised boiler settings and cool washing. A literature review was carried out to assess the impact of these measures on energy consumption.

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The potential savings are estimated by end-use and region to assess the total impact and the resulting decrease in buildings sector emissions.

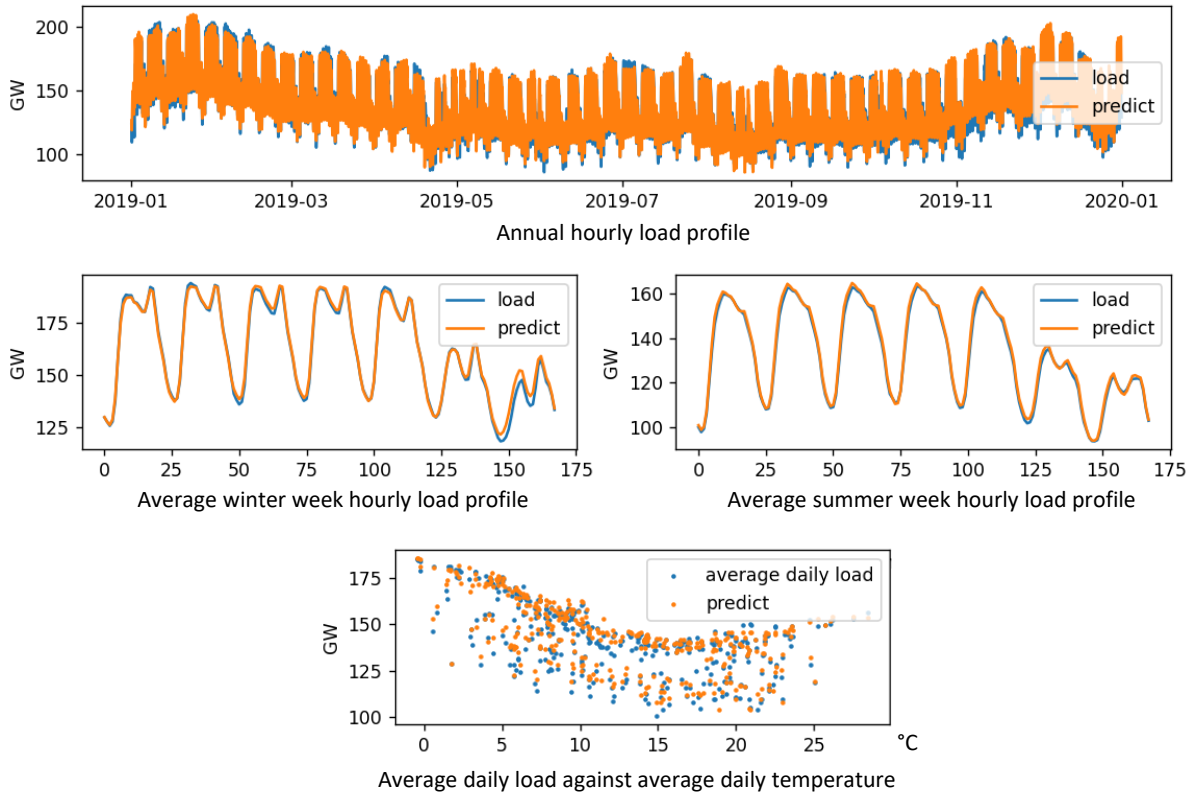
## 3.5 Hourly electricity demand and demand-side response

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

Modelling of hourly electricity demand is undertaken at an end-use level. This 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 affect 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), transport (e.g. road, rail) and agriculture. Load curves are assessed for a full year at the hourly resolution.

Load curve parameters are derived from historical data. A statistical analysis is conducted on historical hourly demand (IEA, 2024b) and heating and cooling degree-day time series (IEA, 2024c). The hourly load dependency on calendar and weather variables is extracted from regression parameters. The weather variables are weighted by population, and temperature thresholds activating cooling and heating demand are determined based on the load response to temperature variations. The statistical analysis is conducted on as many historical years as available, considering the structural changes in electricity demand over time and temporary changes in electricity consumption patterns, such as during pandemic containment measures.

**Figure 3.15 ▷ Thermosensitivity analysis for hourly load curve assessment**



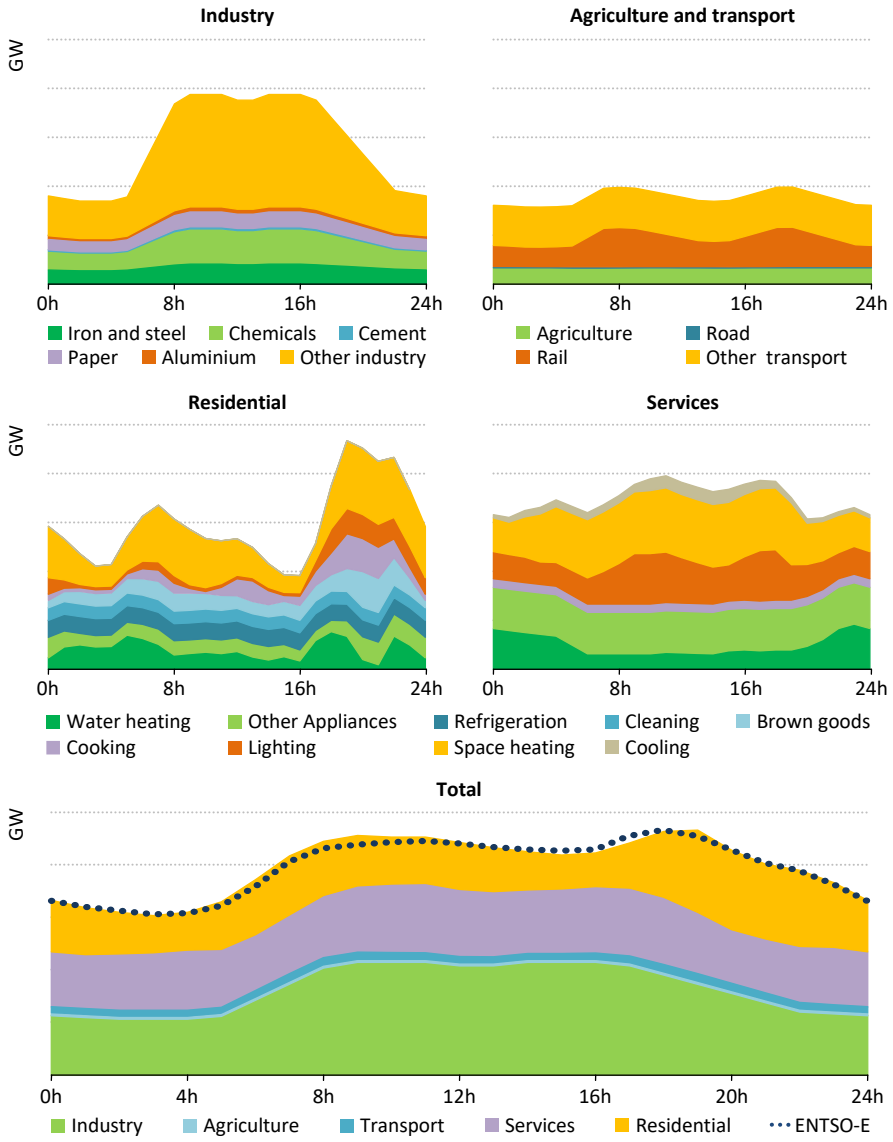

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Average weekly profiles for heating, cooling and non-thermosensitive load are derived from this analysis, along with additional parameters such as the average demand per week of the year. This thermosensitivity analysis allows for the simulation of a region's electricity load curve with a very high level of confidence, considering the impact of variations in weather, most notably temperature (Figure 3.15).

Individual hourly load curves for each electricity end use are generated based on the thermosensitivity analysis, research, and survey data where available. Total space heating and cooling profiles are split between residential and services end uses depending on the hourly activity in each sector. Load curves for other end uses are informed by literature and adjusted to match the total non-thermosensitive profile of the region. Hourly electricity demand for lighting is projected based on daylight times and solar insolation levels.

**Figure 3.16 ▷ 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**




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Notes: GW = gigawatt. The European Network of Transmission System Operators for Electricity (ENTSO-E) curve represents the aggregated load for all countries in the European Union.

Source: IEA analysis based on (ENTSO-E, 2014).

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Finally, load profiles are scaled to the annual end-use demand in the projected year, as simulated in the GEC Model. The hourly load profile can be generated for different weather conditions, by varying the historical temperature time series used as an input. This allows for an assessment of the impact of weather on peak demand and flexibility needs over multiple weather years. An example of the load disaggregation per end use is displayed in Figure 3.16.

The hourly load generation is performed at the country level or at the GEC Model region level. The hourly load model covers all regions across the world and is calibrated either directly from historical load profiles or from literature research and pattern analysis of similar countries.

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, shiftability, controllability and acceptability (Olsen, et al., 2013):

- Shiftability: Share of the load of each end-use that can be shed, shifted or increased by a typical demand-response 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 or shifts.
- Acceptability: Share of the load for a given end-use which is associated with equipment or services for which 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 different levels of social acceptability.

Demand response is included in an hourly electricity model that jointly simulates the dispatch of generation assets, storage, interconnections and demand response to minimise total system operating costs (see Section 4.4 for a description of the hourly model). Demand-response activation considers the flexibility potential (in gigawatts [GW]), the maximum shifting or shedding duration (in hours) and the flexibility activation cost. For transport, additional constraints are developed in the hourly model to reflect the unavailability of unplugged or fully charged EVs for load management.

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# Electricity generation and heat production

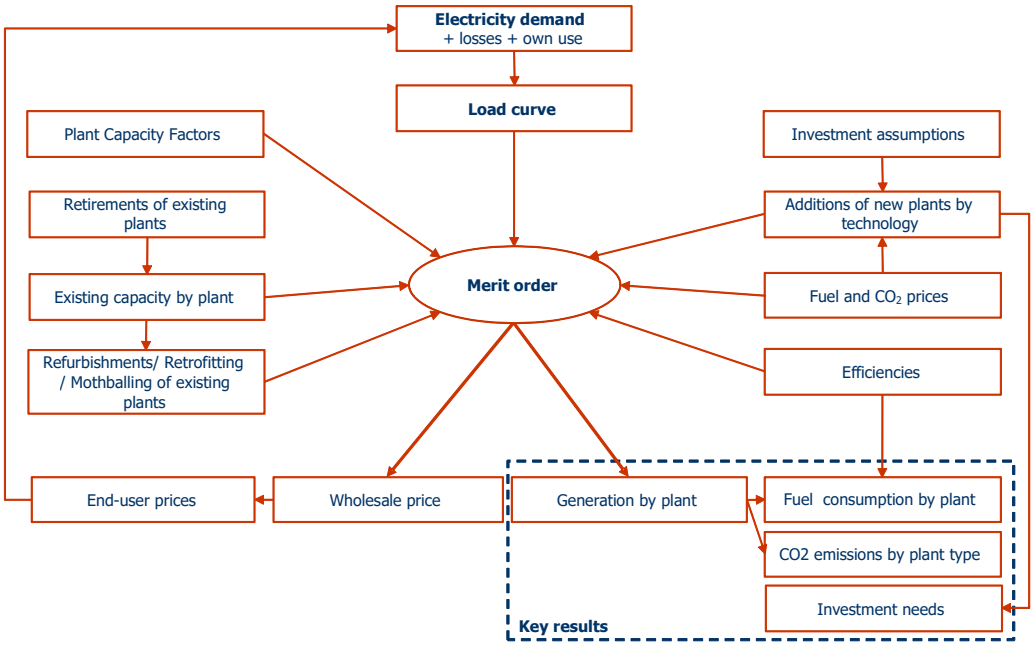
Based on electricity demand, which is computed in all end-use sectors (described in Section 3) and other energy transformation sectors, notably hydrogen production via electrolysis (Section 5), the power generation module calculates the following:

- amount of new generating capacity needed to meet demand growth, 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 and cover transmission and distribution losses and own use
- fuel consumption of the power generation sector
- $CO_2$ emissions from the combustion of fossil fuels and non-renewable wastes, including reductions from the use of carbon capture, utilisation and storage (CCUS) technologies
- 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.

## 4.1 Electricity generation

The structure of the power generation module is outlined in Figure 4.1. 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 maintaining security of supply to cover unforeseen outages.

**Figure 4.1 ▷ Structure of the power generation module**




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Note: $CO_2$ = carbon dioxide.

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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 photovoltaic (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.

### *4.1.1 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 chooses between different technology options on the basis of their regional value-adjusted levelised cost of electricity (VALCOE), which is 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 it 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 overnight capital costs are taken from our own survey of industry views and project costs, together with estimates from the Nuclear Energy Agency (NEA), the IEA and the International Renewable Energy Agency (IRENA, 2026). The assumptions for the weighted average cost of capital (WACC, pre-tax in real terms) reflect market data and survey information provided through the Cost of Capital Observatory (IEA, 2025d), with a range of 4-7% for utility-scale solar PV and onshore wind and 5-8% for offshore wind. A standard WACC was assumed for nuclear power, coal- and gas-fired power plants (8-9% based on the stage of economic development).

The LRMC calculated for any plant is partly determined by its utilisation rate. The model takes into account 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 GEC Model website: 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
- combined-cycle gas turbine (CCGT) with and without CCUS
- open-cycle gas turbine
- integrated gasification combined cycle (IGCC)
- oil and gas internal combustion
- fuel cells

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- bioenergy with and without CCUS
- geothermal
- wind onshore and offshore
- hydropower (conventional)
- solar PV
- concentrating solar power
- marine
- utility-scale battery storage.

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

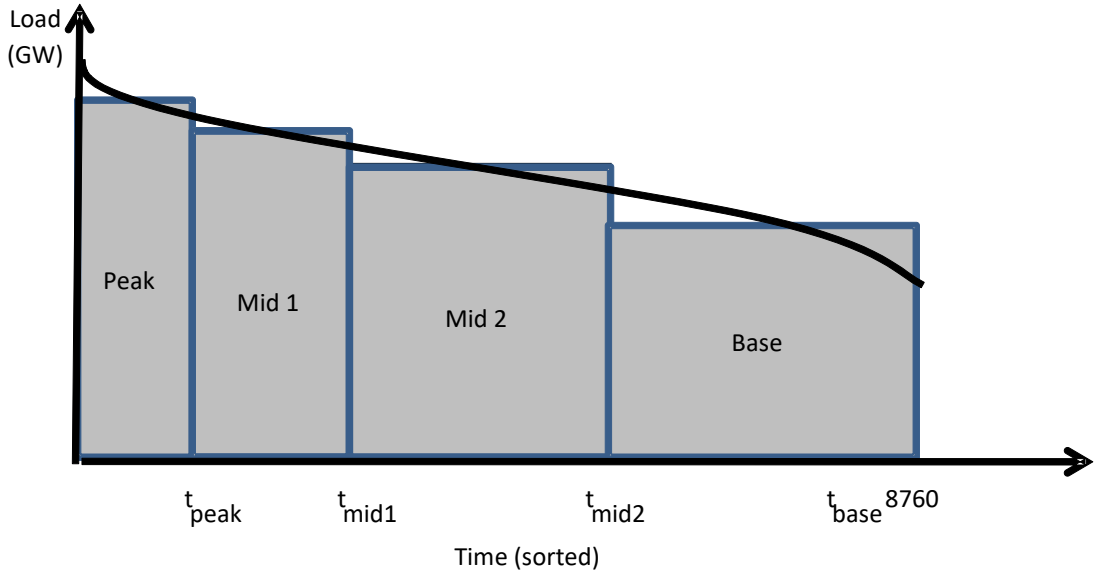
### 4.1.2 Generation volumes

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

- baseload demand, representing demand with a duration of more than 5 944 hours per year
- low-midload demand, representing demand with a duration of 3 128 to 5 944 hours per year
- high-midload demand, representing demand with a duration of 782 to 3 128 hours per year
- peakload 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 4.2). This demand must be met by the available power capacity of each region, which consists of variable renewables – technologies like wind and solar 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). 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 4.2 ▷ Load-duration curve showing the four demand segments**



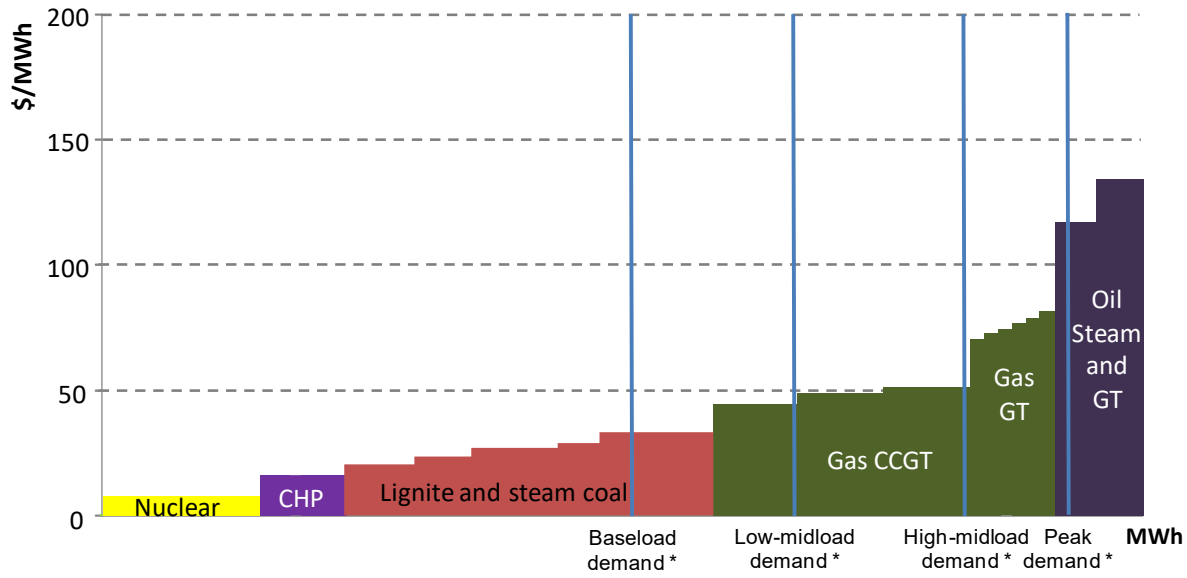

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Note: GW = gigawatt.

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The model subtracts from the demand in each segment any generation from plants that must run – such as some combined heat and power (CHP) plants and desalination plants – and also generation from renewables. For 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. As a result, plants with low variable generation costs – such as nuclear and lignite-burning plants in the example of Figure 4.3 – 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 4.3 ▷ Example merit order and its intersection with demand in the power generation module**




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Notes: MWh = megawatt-hour; CCGT = combined-cycle gas turbine; CHP = combined heat and power; GT = gas turbine. Demand here means demand net of generation by "must-run" plants such as desalination and some CHP plants, and net of generation by renewables.

### *4.1.3 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, concentrating solar power [CSP] without storage, and wind on- and offshore) is taken into account via the capacity credit and the capacity factor in each load segment.

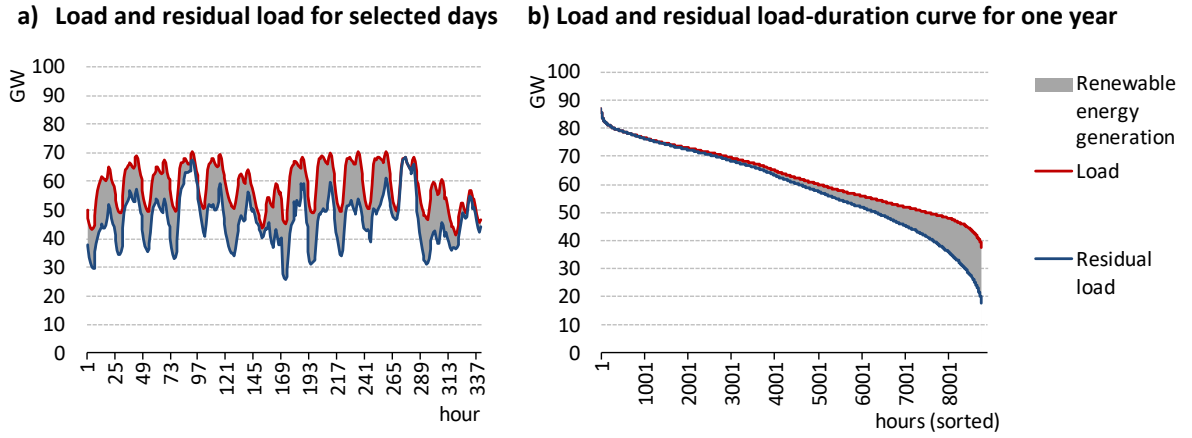
The capacity credit of variable renewables reflects the proportion of their installed capacity that can reliably be expected to be generating at the time of high demand in each segment. It determines how much non-variable capacity is needed in each load segment. The capacity factor gives the amount of 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 on 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 compared to the hourly residual load, which is the electricity load after

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accounting for power generation from variable renewables (Figure 4.4). By sorting the residual load, the levels of average and maximal demand per load segment can be determined. The difference between the levels of the normal load and the residual load gives the impact of variable renewables on the power generation and capacity needs.

**Figure 4.4 ▷ Example electricity demand and residual load**




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The capacity factor of variable renewables (varRE) per load segment can be calculated based on 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:

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

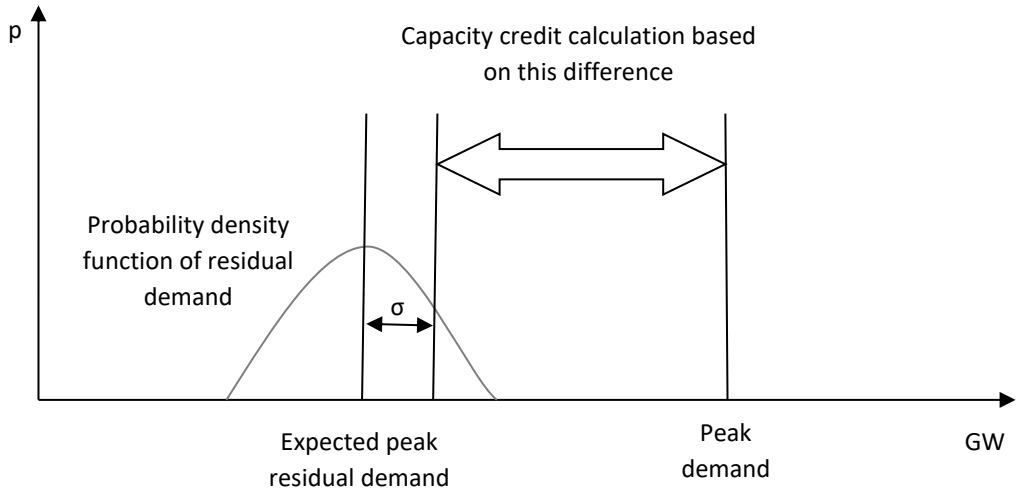
Meteorological data (wind speed and solar irradiation) for several years were used for the capacity credit calculation. In aggregating the results of capacity credit obtained from different years of meteorological data, as a first-order approach, it was assumed that the annual peak residual demand is normally distributed. The capacity credit was calculated based on the difference between peak demand and the point one standard deviation above the peak residual demand (Figure 4.5).

The meteorological data stem from the following sources:

- World Wind Atlas: Global dataset of hourly wind speeds at 10-metre height, 1979-2009.
- Wind supply time series for the western and eastern United States as derived by NREL (2010a) and NREL (2011).
- Wind and solar supply time series for Europe-27 as provided by Siemens AG (Heide et al., 2010) for each major region in Europe. Original meteorological wind speed stems from reanalysis data (WEPROG, 2010).
- Hourly solar irradiation data from satellite observations for the United States (NREL, 2010b).
- Estimation of solar irradiation based on solar height (Aboumahboub et al., 2010).

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**Figure 4.5 ▷ Capacity credit calculation**




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## 4.2 Value-adjusted levelised cost of electricity

Major contributors to the LCOE include overnight capital costs; capacity factor that describes the average output over the year relative to the maximum rated capacity; the cost of fuel inputs; and O&M. Economic lifetime assumptions are 25 years for solar PV, onshore and offshore wind. Weighted average cost of capital (WACC) assumptions reflect market data and survey information provided through the Cost of Capital Observatory (IEA, 2025d), with a range of 4-7% for utility-scale solar PV and onshore wind and 5-8% for offshore wind. A standard WACC was assumed for nuclear power, coal- and gas-fired power plants (8-9% based on the stage of economic development).

The VALCOE is a metric for competitiveness for power generation technologies, building on the capabilities of the GEC Model hourly electricity model. It is intended to complement the LCOE, which captures relevant information only 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 between variable renewables and dispatchable thermal technologies, taking account of both cost and value.

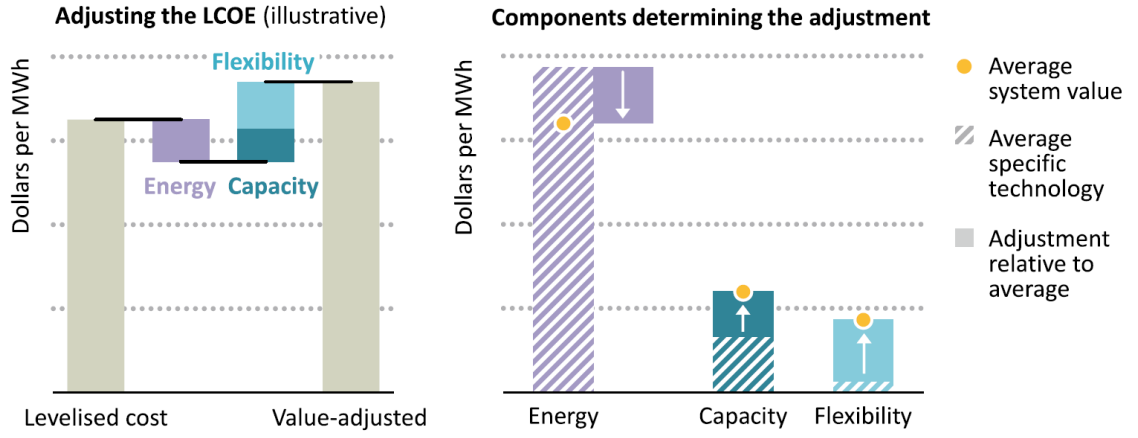
The VALCOE builds on the average LCOE (or LRMC) by technology, adding three elements of value: energy, capacity and flexibility. For each technology, the estimated value elements are compared against the system average to calculate the adjustment (either up or down) to the LCOE. After adjustments are 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 4.6). The VALCOE is applicable in all systems, as energy, capacity and flexibility services are provided and necessary, 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.

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 megawatt-hour (MWh), but also relatively high value per MWh. For baseload technologies, value tends to be close to the system

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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.

**Figure 4.6 ▷ Moving beyond the levelised cost of electricity to the value-adjusted levelised cost of electricity**




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Note: LCOE = levelised cost of electricity.

The VALCOE is composed of LCOE plus energy, capacity and flexibility values. It is calculated 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 and the system average unit $[\bar{E}]$. $[E_x]$ is calculated as follows:

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

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 Europe, China, India, Indonesia and the United States. 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:

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

The capacity credit reflects the contribution to system adequacy and 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.

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The basis capacity value is determined based on simulation of a 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 the previous year
- wind and solar PV = aligned with the latest performance data from IRENA (2026) and other sources, improving over time due to technology advancements
- hydropower and other renewables = aligned with the latest performance data by region and long-term regional averages.

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

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

- 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 European Union and United States. The flexibility value is assumed to increase with rising variable renewable energy (VRE) shares, up to a maximum equal to the full fixed capital recovery costs of a peaking plant.

#### *Advantages and limitations of the value-adjusted levelised cost of electricity*

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 on, or 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 as some real-world applications. The VALCOE is most closely related to the System LCOE, which provides a comprehensive theoretical framework for assessing system value beyond the LCOE (Ueckerdt, Hirth, Luderer, & Edenhofer, 2013). The VALCOE and System LCOE are similar in scope, and re-arranging terms can align significant portions of the computations. Optimisation models implicitly represent the cost and value of technologies through standard profitability metrics, such as net present value and internal rates of return, but they may be limited by the scope of costs included, such as those related to ancillary services. Other long-term energy modelling frameworks have incorporated cost and value metrics in capacity expansion decisions, such as the Levelised Avoided Cost of Electricity built into the National Energy Modeling System used by the US Energy

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Information Administration. In policy applications, for example in the 2017 clean energy auction schemes in Mexico, average energy values for prospective projects were simulated and used to adjust the bid prices, seeking to identify the most cost-effective projects. As clean energy transitions progress around the world, experience with higher shares of wind and solar PV in large systems will increase and provide opportunities to refine the VALCOE and other metrics of competitiveness.

## 4.3 Electricity transmission and distribution networks

The model calculates expansion and replacement of electricity transmission and distribution networks along with associated investment per region. 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.

Electricity networks in the GEC Model are divided into several categories: five distinct voltage ranges, overhead line or underground cable, and alternating current (AC) or direct current (DC), creating 20 possible line or cable types. This allows for increased granularity on equipment costs, material needs and regional differences. This information is then used in the model to understand current and projected composition of networks, as line expansion projections carry the same level of detail on line and cable type. Because of this, costs that are region- and line-specific can be paired with line and cable type to create a model representation of investment needs for each region's grid. In addition, this detailed view of line and cable type is then paired with materials use per kilometre (km), notably with critical minerals, to form projections of materials demand due to the growing electricity network.

The need for new electricity network line lengths is driven by three factors: to replace existing lines nearing the end of their technical lifetime, to support increasing electricity demand and to integrate additional renewables in the power sector.

### *Line replacement due to ageing infrastructure*

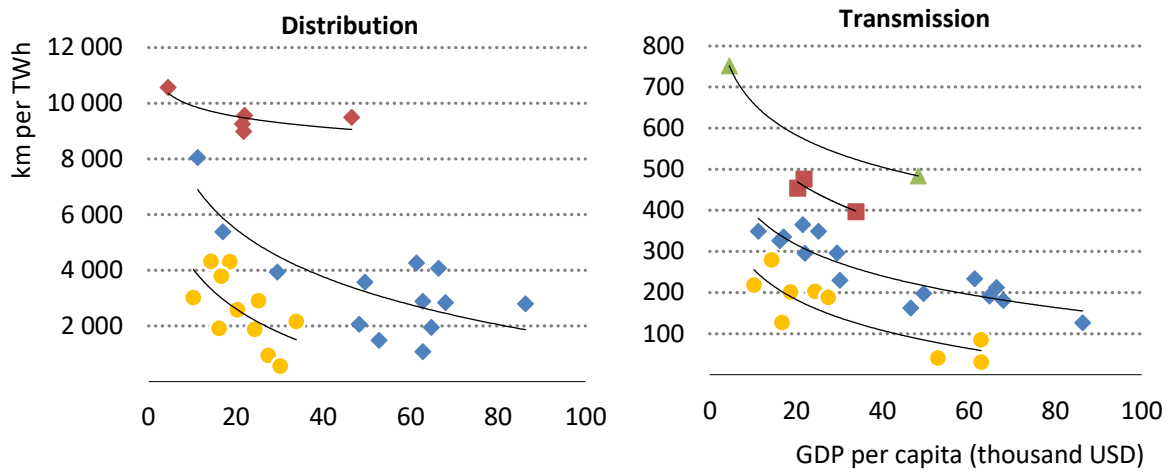
Assuming an average lifetime of 40 years for lines and cables, the model calculates annual replacements accordingly. While this does not increase the overall size of the network, it adds millions of kilometres of new lines and cables each year that must be accounted for in terms of investments and material demand, as well as for project planning.

### *Line length expansion due to electricity demand growth*

Network expansion increases alongside growth in electricity demand. To represent this, a dynamic relationship between network expansion per unit of demand growth and GDP per capita was created. In this, the km of line length per terawatt-hour (TWh) of demand for each region is used with the GDP per capita for the given region. This produced equations that represent these relationships, wherein regions with similar growth relationships were grouped together. As the network growth rates differ between the distribution and transmission levels, these relationships were derived for each, yielding multiple sets of alpha and beta parameters that can be used with finer granularity.

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**Figure 4.7 ▷ Electricity network expansion per unit of electricity demand growth by GDP per capita**




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Note: TWh = terawatt-hour; km = kilometre; GDP = gross domestic product.

### *Line length expansion due to renewables*

A considerable share of the capacity additions projected over the modelling horizon is from renewables. The 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 increased distribution capacity needs.

Because the introduction of large quantities of remote or variable renewables was not a marked feature of the historical development of electricity networks (except for regions where remote hydroelectricity represents a large proportion of the generation mix), adding more renewables is likely to increase the average length of network additions.

Line expansion is being driven by two factors: the transmission lines that connect solar and wind farms to the grid, and reinforcement requirements within the grid. A factor for the average connecting line length was derived from the average line length connecting past utility-scale solar PV, onshore wind and offshore wind projects. The added capacity from these renewable energy technologies is multiplied by the historical relationship to obtain related line extensions.

The grid reinforcements are based on an IEA study conducted in countries with high renewable energy development. Up to a threshold of the share of renewable generation, there is no need for grid improvements. An increase in the share beyond this threshold leads to additional lengths to reinforce the grid, based on the literature and projected shares of renewables by region and scenario.

The estimation of distribution grid extensions for renewables contains more uncertainties than the transmission grid, as less data or fewer studies are available on the technically complex distribution network, 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 from distributed generation, such as solar PV in buildings, exceeds local demand and is fed back to the system.

### *Transformer capacity expansion due to electricity demand and supply growth*

Transformer capacity is based on historical data associated with the power generation capacity in each GEC Model region. For the calculation of transformer capacity growth, new power capacity is taken into consideration, whereas all small-scale solar PV is deducted as it is assumed that most output will be used locally.

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Large-scale solar PV will be connected to the distribution network and is accounted for. Part of additional battery storage capacity is deducted as it will reduce the flow of power through the grid and therefore the need for transformer capacity.

### *Transformer replacement due to ageing*

Assuming an average lifetime of 40 years for transformers, annual replacements are calculated accordingly. While this does not increase the overall capacity in the network, each year it adds transformer capacity that must be accounted for in terms of investment and material demand.

### *Electricity network investment*

Investments for electricity networks are composed of those related to the three main drivers of line length expansion: increasing demand, replacements and increasing renewables. In addition, they include investments due to components other than line length, such as grid-forming requirements and transmission-level reinforcement. For the line length components of the investment, which comprise the majority of overall network investments, the model calculates this as the network expansion in km due to a given driver multiplied by the unit cost for each line and cable type.

Grid-forming requirements are also incorporated into the electricity network representation, related to the extent of the shift to variable renewables in the projections. Variable renewables lack mechanical inertia as they connect to the network via a converter. Inertia comes from the large rotating masses in the generators in power plants and is necessary to keep the network stabilised, especially in case of fault events. With the rising share of variable renewables, the network needs grid-forming stabilising technology from the Flexible AC Transmission Systems family. The calculation for this investment is based on deployment needs realised in countries with a high share of renewables. The investment is driven by the expansion of renewables generation above a minimum level and increases based on assessed needs in each region. Below the minimum level, the grid remains stable without additional measures.

Each of the electricity network equipment unit costs has been created using an average of project- and national-level costs, collected from publications that detail costs per km based on corresponding line and cable type. They represent costs from several regions globally, allowing for a balanced view of region-specific costs. These costs are then tailored further, creating a series of 20 different costs per km for each region. Similarly, replacement costs are line- and region-specific. For all types and regions, replacement costs are lower than those of new lines, as permitting, land and many of the capital costs do not need to be redone. However, region-specific discounters are used to differentiate material use and labour costs by region, two factors that can greatly influence costs per km. Bringing together all of these costs and drivers for network expansion, the model calculates overall network investment with the following equation for each of the 20 line and cable types:

$$
\begin{aligned}
&Annual\ transmission\ investment\ by\ region = \\
&\sum_{V,P,C} [cost\ new\ lines_{V,P,C} \\
&* \begin{pmatrix} \Delta\ electricity\ demand * (\alpha * \ln(GDP\ per\ capita) + \beta) * grid\ composition_{V,P,C} \\ + \sum_{R} (renewables\ additions_{R} * \gamma_{V,P,C}) \\ + \Delta\ share\ of\ variable\ renewables * \psi * total\ transmission\ length_{V,P,C} \end{pmatrix} \\
&+ cost\ replacement_{V,P,C} * lines\ replacement_{V,P,C}] \\
&+ cost\ STATCOM * \phi * \Delta\ share\ of\ variable\ renewables\ installed * total\ power\ capacity
\end{aligned}
$$

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$$Annual\ distribution\ investment\ by\ region =$$

$$\sum_{V,P,C}\left[cost\ new\ lines_{V,P,C} * \left(\begin{array}{c}\Delta\ electricity\ demand * (\alpha * \ln(GDP\ per\ capita) + \beta) * grid\ composition_{V,P,C} \\ + \sum_{R}(renewables\ additions_{R} * \gamma_{V,P,C})\end{array}\right) + cost\ replacement_{V,P,C} * lines\ replacement_{V,P,C}\right]$$

Where:

- $V$ is voltage level band
- $P$ is position (overhead, underground)
- $C$ is current (AC or DC)
- $R$ is the renewable energy technology
- $grid\ composition_{V,P,C}$ is the historical shares of the grid by voltage, position and current
- $\alpha$ , $\beta$ are dimensionless variables in the equation relating demand growth to GDP per capita, derived from historical data by region
- $\gamma$ is the additional line lengths required to connect new renewables capacity additions, measured in km per GW, by voltage, position and current
- $\psi$ is the dimensionless factor of additional transmission network requirements due to high shares of variable renewables, where the share exceeds a minimum threshold
- $\Delta\ electricity\ demand$ is the annual increase in electricity demand in the region
- $\Delta\ share\ of\ variable\ renewables$ is the annual increase in share of variable renewables in total installed capacity
- $lines\ replacement_{V,P,C}$ are the lines to be replaced, in km, defined as those reaching 40 years of use
- $cost\ STATCOM$ is the cost of STATCOM devices (static synchronous compensators)
- $\phi$ is the dimensionless factor of additional grid-forming requirements due to high shares of variable renewables, given that the share of renewables exceeds a minimum threshold.

The current annual expenditures of both the distribution system operator (DSO) and transmission system operator (TSO) are examined across various regions, and these figures are linked to the calculated investment. The investment in grid infrastructure does not adhere to a spending model that spreads the investment over time, in contrast to the approach used for calculating investments in power generation.

## 4.4 Hourly electricity model

To assess power system operations with rising shares of variable renewables (VRE) and temperature-sensitive end uses such as electric heating and cooling, an hourly model was developed for the *World Energy Outlook 2023* (*WEO-2023*) and expanded for the *WEO-2025*. Building on the annual projections of the GEC Model, the model makes it possible to explore the issues that arise as the share of VRE grows. These include power system flexibility needs on timescales from hours to days, weeks and seasons, and how these needs can be met at least cost. They also include system adequacy during periods of low wind and solar output or high demand, VRE curtailment, the role of storage, demand response and hydrogen, and the value of different technologies to the system. The model was built in Python using the *PyPSA* open-source environment for energy system modelling[1] and is solved using linear optimisation. It represents all hours in the year, setting the objective of meeting electricity demand in each hour at the lowest possible total system cost while respecting operational constraints. Power plants, energy storage technologies, demand response and electrolysers are optimised jointly, so that each is operated in the way that minimises total system cost and thus maximises its value to the system. The model covers China, Europe, India, Indonesia and the United States.

[1] https://pypsa.org/

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All 106 power plant types recorded in the GEC Model and their installed capacities are represented in the hourly model. These include existing and new fossil-fuelled power plants, nuclear plants, battery storage and 16 different renewable energy technologies. The fleet of power plants that is available in each year is determined in the GEC Model and differs by scenario, depending on the prevalent policy framework. These plants are dispatched (or chosen to operate) on the basis of their short-run marginal operating costs, to the extent required to meet demand. These costs are mainly determined by fuel costs as projected in the GEC Model. The dispatch operates under constraints. Minimum generation levels ensure the flexibility and stability of the power system and meet other needs (such as heat supply from CHP plants). The variability of renewable resources (such as wind and solar) determines the availability of variable renewables and, hence, their maximum output at any point in time. Ramping constraints also apply, derived from the level of output in the preceding hour and the characteristics of different types of power plants. The model also simulates reserve procurement and can operate in unit-commitment mode. In this mode, power plants are represented as discrete units, with constraints and costs related to start-up and shutdown times, minimum load levels and minimum downtime requirements.

Key inputs to the model include detailed hourly production profiles for wind power and solar PV in each region. An improved methodology to estimate these profiles was developed for the *WEO-2025*. It considers the technical characteristics of wind turbines and solar PV systems and uses detailed information on the current and projected locations of wind and solar generators. It converts weather data such as wind speeds, solar irradiance and temperature into wind and solar PV availability profiles. Because generators are distributed across each region, the profiles capture the smoothing effect of geographically dispersed generation. Production profiles for run-of-river hydro and inflow profiles for reservoir hydro are generated using the *Atlite* open-source Python library[2] (Hofmann, Hampp, Neumann, Brown, & Hörsch, 2021), which translates runoff into hourly run-of-river output and reservoir inflows. To capture variability across years, including extreme events, the model uses data for 30 historical weather years[3] (1987-2016). These data cover both weather-dependent renewables and temperature-dependent demand and is taken from the ERA5 reanalysis dataset of the European Centre for Medium-Range Weather Forecasts, which covers the entire globe at 30-km resolution (ECMWF, 2026).

On the demand side, the model uses the hourly load profiles generated by the hourly demand model described in Section 3.5. These are built for each electricity end use in each sector, based on a thermosensitivity analysis of historical demand. They are then scaled to the annual end-use demand projected in the GEC Model for the relevant scenario and year. Because the load model can vary the temperature input, demand profiles are generated for each weather year. Variations in renewables output and in temperature-sensitive demand, such as space heating and cooling, are therefore represented consistently. The demand-response potential of each end use is also taken from the hourly demand model described in Section 3.5. Each potential is characterised by the flexible capacity, the maximum duration of load shifting or shedding, and the activation cost. Additional constraints reflect the availability of electric vehicles for load management.

The model represents the main sources of flexibility needed to integrate growing shares of variable renewables: flexible generation, storage, demand response and transmission. Because these are optimised together, VRE curtailment, demand-response activation and storage operations are determined jointly, based on the available potential in each hour and the price differentials across hours. To capture the long-term impact of weather-related variability in systems dominated by renewables, the model includes a detailed representation of reservoir and pumped storage hydro, hydrogen electrolysers and hydrogen storage. Dispatch of hydro reservoirs and pumped storage is constrained by water levels. Natural inflows are derived from runoff and the hydrological basins of each hydropower plant. To capture interactions between the electricity and hydrogen systems, the model optimises the operation of grid-connected electrolysers, hydrogen storage and thermal power plants using hydrogen. It also takes into account hydrogen production from off-grid electrolysers connected to

[2] https://github.com/PyPSA/atlite

[3] A weather year is a set of weather parameters, such as temperature, solar radiation, wind speed and precipitation, compiled from historical records to create curves of hourly loads and renewables output.

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dedicated renewables, as well as demand profiles for other uses of hydrogen. To reflect constraints in the transmission system, each modelled region is split into several nodes that can exchange electricity with each other. These exchanges are limited by the overall transmission capacity between nodes. Grid constraints within each node are not represented.

Among the important model outputs is the resulting hourly market price, which can drop to zero in 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, the model calculates the revenues received in each hour by each type of plant. This creates a basis for calculating the value to the system of different technologies, including VRE. The model also provides hourly operating information for each plant type, including VRE curtailment, fuel costs and the associated GHG and pollutant emissions. It thereby enables the assessment of the integration needs arising from growing shares of renewables.

#### *Assessing flexibility needs*

Flexibility can be defined as the ability of a power system to reliably and cost-effectively manage the variability and uncertainty of supply and demand across all relevant timescales. Flexibility needs can be seen as the balancing effort required to smoothen the residual load over a given timescale (which could then be satisfied with baseload capacity). To account for specific flexibility needs of the system depending on the timescale, we distinguish between short-term and seasonal flexibility needs. Short-term flexibility needs are calculated as the average hourly ramp of the residual load (difference between a given hour and the previous hour) over the top-100 hours with the highest upward ramps, divided by the average hourly electricity demand for the year (electricity demand in this case does not include battery charging, pumped storage pumping or net exports). Seasonal flexibility needs are assessed by computing the difference between the weekly and annual average of the residual load, divided by the annual electricity demand.

Short-term flexibility needs are computed as follows:

$$Ramp(t) = ResidualLoad(t) - ResidualLoad(t - 1h)$$

$$FlexibilityNeeds_{year,short-term} = \frac{\frac{\sum_{t\in\{t_1,t_2\ldots t_{100}\}\ with\ Ramp(t_i)\geq Ramp(t_{i+1})} Ramp(t)}{100}}{\frac{AnnualElectricityDemand_{year}}{8760}}$$

Seasonal flexibility needs are computed as follows:

$$FlexibilityNeeds_{year,seasonal} = \frac{\sum_{t\in year}|ResidualLoadWeeklyAvg(t) - ResidualLoadAnnualAvg(t)|}{AnnualElectricityDemand_{year}}$$

## 4.5 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 GEC Model. 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 LRMC, 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) developed by the KTH Royal Institute of Technology, to cover in detail 44 countries in sub-Saharan Africa (KTH Royal Institute of Technology, 2014). 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, is also represented in the model, with its projected use tied to the quality of the on-grid power supply.

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## 4.6 Renewables and combined heat and power modules

The projections for renewable electricity generation and CHP are derived in separate sub-modules.

### *4.6.1 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.

### *4.6.2 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, CSP, geothermal electricity, wind and marine) in each of the GEC Model regions.[4] Policy targets are often for specific technologies; for example, over 130 countries had support policies in place to expand the use of solar PV and wind as of 2020. Other policies 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. Technology competitiveness and resource potentials drive the relative contributions where policies specify a broad target that includes renewables. Technology competitiveness is based on the VALCOE (see Section 4.2) and applies equally to comparisons among renewable energy technologies and a broader set of technologies. Resource potential is considered on a regional basis for each renewable energy technology (see Box 4.1). Beyond the reach of policy targets, the critical considerations for renewables deployment are technology competitiveness and resource potentials. 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 generation from all projects in operation within a given year.

As of *WEO-2026*, the power system module in the GEC Model has been enhanced to make the treatment of the curtailment of variable renewables (wind and solar PV) explicit in the model and reporting. In previous editions, reported wind and solar PV generation reflected available output (i.e. potential electricity generation before considering curtailment). Curtailment was modelled endogenously within the dispatch and balancing framework – ensuring that electricity supply met demand in all time periods – but was not reported separately.

Under the upgraded framework, generation is now reported as realised output, i.e. non-curtailed generation. This aligns reported generation more closely with system outcomes and improves transparency on the contribution of renewables.

Several related enhancements accompany this change:

- Improved curtailment representation: Curtailment better reflects power system conditions linked to the contribution of solar PV and wind power.
- Technology allocation: The model explicitly allocates curtailment between wind and solar PV.

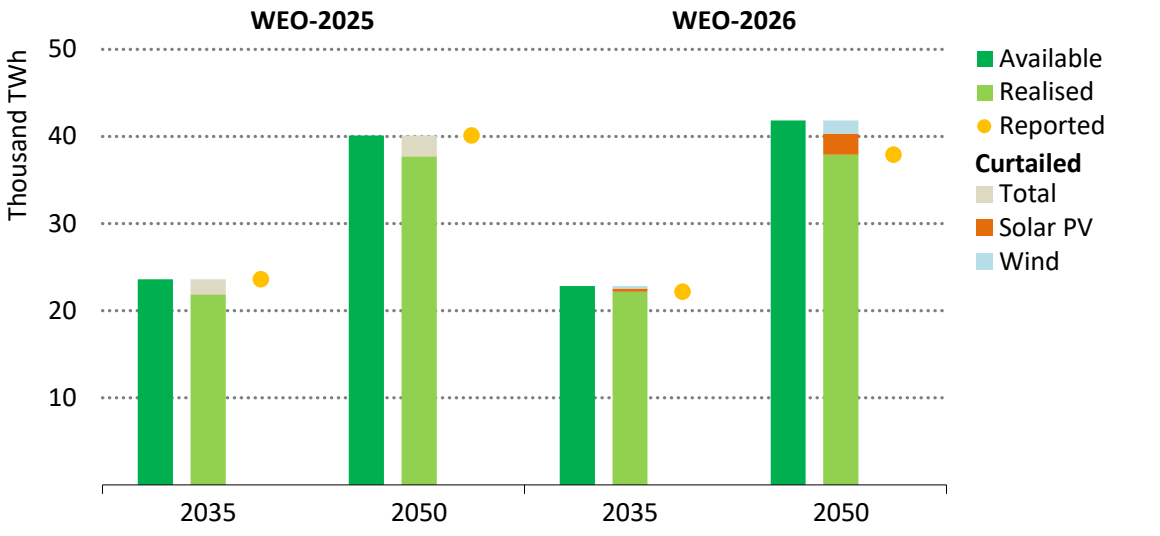
[4] A number of sub-types of these technologies are modelled individually, as follows. Biomass: small CHP, medium CHP, electricity-only power plants, biogas-fired, waste-to-energy fired and co-fired plants. Hydro: large (≥10 MW) and small (<10 MW). Wind: onshore and offshore. Solar PV: large-scale and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

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- Consistent reporting: Published output metrics now explicitly distinguish between available and realised generation.

These upgrades were implemented to (i) improve the clarity and interpretability of WEO results, (ii) elevate curtailment as a key policy and system design consideration, and (iii) leverage the increasing availability of empirical data on curtailment across a growing number of countries.

**Figure 4.8 ▷ World renewables generation in the Stated Policies Scenario in the *WEO-2025* and *WEO-2026*, 2035 and 2050**




Note: TWh = terawatt-hour; PV = photovoltaics; WEO = World Energy Outlook.

This change is important when comparing *WEO-2025* and *World Energy Outlook 2026* (*WEO-2026*) reported results. Measured as available generation, renewables have been revised slightly downwards in 2035 at the global level in the *WEO-2026* STEPS and revised upwards in 2050. As curtailment and available generation were not published previously, they cannot be compared directly across editions.

Overnight investment needs for renewables are calculated based on the deployment of renewables and evolving technology costs. Our modelling, in all scenarios, incorporates 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 is commonly expressed through the LCOE. While technology learning is integral to the approach, the GEC Model does not try to anticipate technology breakthroughs.

**Box 4.1 ▷ 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:

- 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 resource, based on current scientific knowledge.

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- The *technical* potential can be derived by observing boundary conditions such 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 R&D, conversion technologies might be improved and the technical potential increased.

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

#### *Offshore wind technical potential*

In collaboration with Imperial College London, a detailed geospatial analysis was undertaken for the *World Energy Outlook 2019* (*WEO-2019*) to assess the technical potential for offshore wind worldwide. The study was among the first to use the ERA5 reanalysis dataset which provides four decades of historical 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, 2008). 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 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

To assess the global technical potential, best-in-class turbines were chosen with specific power of 250, 300 and 350 watts per square metre ($W/m^2$) that corresponds to low-medium, medium and high wind speeds. The power curves of these turbines were used 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 megawatts (MW), for which data are not yet available (Saint-Drenan, 2020).

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.

## 4.7 Hydrogen and ammonia in electricity generation

Low-emissions 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 GEC Model, 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

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hydrogen and/or ammonia, and the uptake of new designs that can blend 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 GEC Model 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 supply module to inform the overall demand for hydrogen production.

## 4.8 Battery storage

Battery storage in the GEC Model provides an important source of power system flexibility, particularly when flexibility needs increase due to evolving electricity demand patterns and rising shares of variable renewables. The model incorporates both utility-scale and behind-the-meter battery storage. Utility-scale battery storage systems are directly connected to the grid. Behind-the-meter battery storage refers to applications at the distribution level, installed at residential, commercial and industrial end-user locations. These batteries are connected to buildings and rooftop solar PV systems, behind the electricity meter and buildings' own connection to the power grid.

In the hourly model, charging and discharging patterns for utility-scale batteries are optimised based on price arbitrage opportunities (i.e. charging when prices are low and discharging when prices are high). Utility-scale battery storage volumes range from one to eight hours in duration (referring to the number of hours a full battery takes to discharge fully 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 certain threshold, which is set based on factors such as upfront capital costs, the expected number of cycles over the battery's lifetime and round-trip efficiency. As with other electricity sector technologies, utility-scale battery investment decisions are based on the 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 be either stand-alone or paired directly with power plants, such as wind and solar PV.

Investments in behind-the-meter batteries are largely driven by the savings potential they provide to electricity consumers. Consumers tend to realise the greatest benefit when combining behind-the-meter batteries with rooftop solar PV and in regions with dynamic time-of-use pricing. Consumers will be further incentivised to invest in solar PV and behind-the-meter batteries, and to make the fullest use of them, if grid feed-in is not prohibited or restricted, and if selling back excess solar PV generation is remunerated at full retail prices. Strong incentives can also reduce overall peak demand on the grid. In reducing grid reliance, behind-the-meter batteries can also allow consumers to downsize the grid connection itself, minimising another monthly charge.

In the model, the deployment of behind-the-meter batteries is linked to the deployment rate of rooftop solar PV based on average country- or region-level attachment rates (the ratio of behind-the-meter battery storage to rooftop solar PV capacity). These attachment rates are estimated and projected forward considering country- and region-specific regulatory environments and tariff structures, the development of retail electricity prices, subsidies for behind-the-meter storage and the expected cost of behind-the-meter battery storage systems.

Battery storage capital costs are projected to decline over time. Technology cost reductions are calculated based on learning rates from existing literature, applied to the battery pack and to auxiliary components such as inverters, as well as other overhead costs. For battery packs, projected costs are driven not only by the deployment of batteries in the power sector but also by the demand for batteries across all sectors, with by far the largest volumes used in electric vehicles. For the other components of battery storage systems, the decline in cost is estimated based on the cumulative capacity additions of battery energy storage systems themselves.

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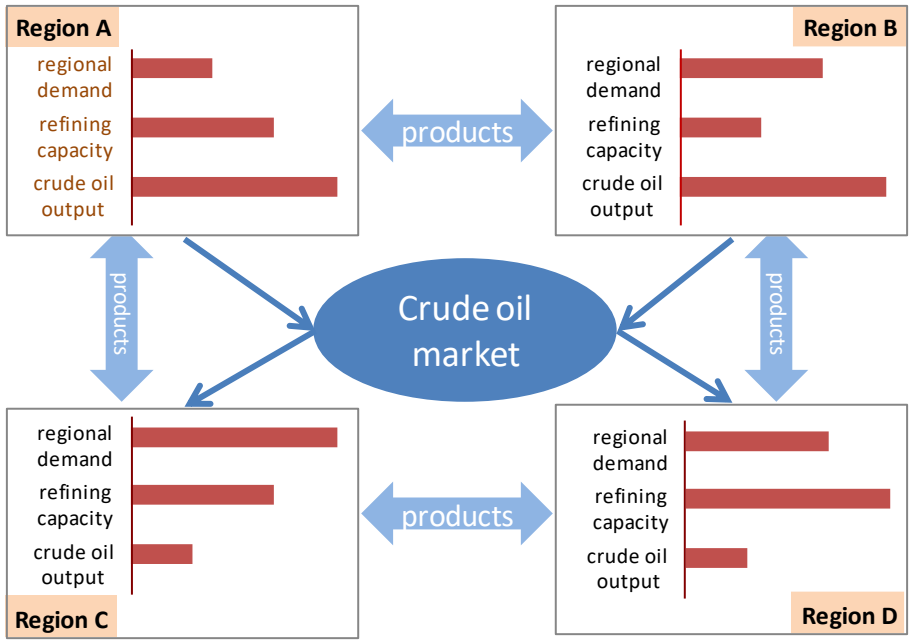
## 5.1 Oil refining and trade

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 and 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 the supply of light oil 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 product categories for all sectors except road transport and aviation. The latter are provided by the GEC Model's transport demand model.

Projections for refining sector activity are based primarily on refining capacity and utilisation rates. Refining capacity consists of crude distillation units and condensate splitters. Refining capacity is based on 2026 data from the IEA Oil Markets Division medium-term outlook. Capacity expansion projects that are currently announced are assessed individually to identify only the projects that are 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 2031, new capacity expansion is projected based on crude availability and product demand prospects for each of the regions specified below. Capacity at risk is defined as the difference between refinery capacity and refinery runs from the current base year, with the latter including a 14% allowance for downtime. Projected shutdowns beyond those publicly announced are also counted as capacity at risk.

**Figure 5.1 ▷ Schematic of refining and international trade module**




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Utilisation rates are determined by domestic demand, product yields and refinery configuration (e.g. complexity). Among oil-importing regions, priority call on international supply of crude oil is given to those where demand is

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growing: robust domestic demand is effectively a proxy for refinery margins, which are not explicitly calculated or used by the model.

Oil supply and demand projections are provided by the GEC Model'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, LPG, ethane and light naphtha from natural gas liquids (NGLs), 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 that of 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: ethane, LPG, naphtha, gasoline, kerosene, diesel, heavy fuel oil (HFO) and other products (which include petroleum coke, refinery gas, asphalt, solvents and wax). Crude oil trade positions and refined products trade balances follow the GEC Model's demand model granularity of 29 individual countries or regions (Figure 5.1).

## 5.2 Coal-to-liquids, gas-to-liquids and coal-to-gas

Coal-to-liquids (CTL), gas-to-liquids (GTL) and coal-to-gas (CTG) technologies chemically convert coal and natural gas into other liquid and gaseous hydrocarbons. For instance, the Fischer-Tropsch process turns coal and natural gas into synthetic fuels through a series of chemical reactions. To that end, an essential first step in this process is to transform coal and natural gas into synthetic gas (also called syngas). Syngas is a mixture of carbon monoxide and hydrogen obtained by coal gasification and the dry reforming of methane. Syngas can also be used to produce methane through the Sabatier reaction and is therefore a means of converting coal into gas.

Countries with large coal or natural gas resources (e.g. China) may resort to CTL, GTL or CTG to bolster their energy security and sovereignty. However, because these technologies are capital-intensive, low-cost coal or natural gas is essential to make the final products competitive. For this reason, the few existing and planned projects remain concentrated in a handful of countries. In the GEC Model, projections are consistent with the status of the projects (e.g. under construction or planned) and are updated every year on a project-by-project basis. Energy-related $CO_2$ emissions are accounted for, and technologies can be fitted with carbon capture, utilisation and storage (CCUS).

## 5.3 Hydrogen production and trade

Hydrogen in today's energy system is predominantly used as a feedstock rather than a fuel, especially when it is used as a purified hydrogen gas. These existing applications are mostly in the refining and chemicals sectors and are part of the industry and refining modules of the GEC Model. Most hydrogen for these existing applications is today produced onsite by steam methane reforming of natural gas or coal gasification without CCUS, while in the 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. This onsite production of hydrogen is modelled within the industry and refining modules of the GEC Model.

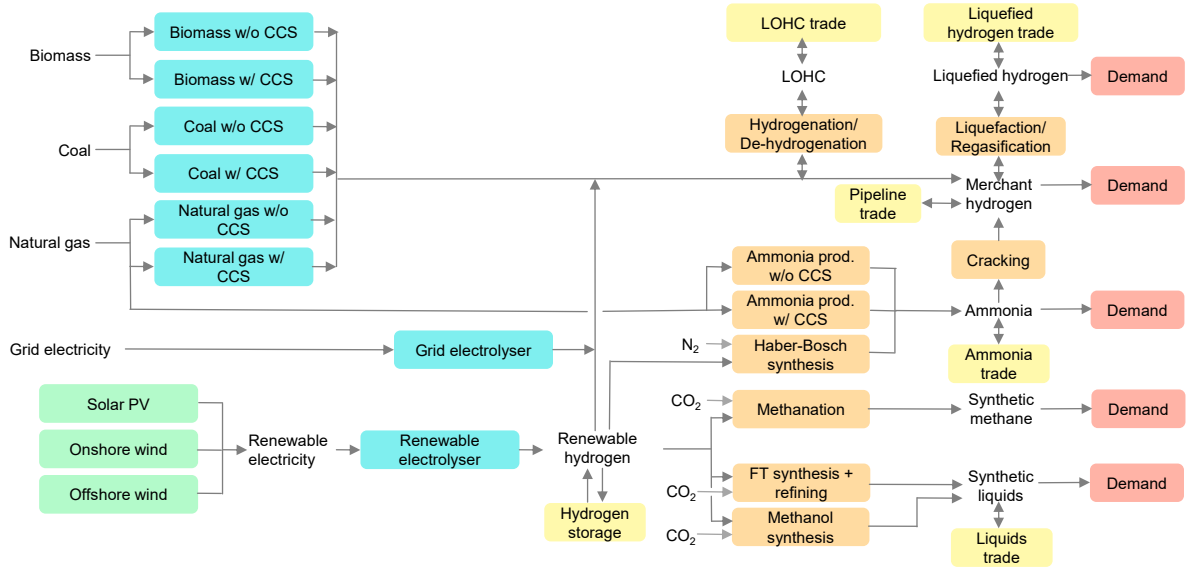
The hydrogen production and supply module of the GEC Model (hereafter the "hydrogen supply module") covers the production of merchant hydrogen and hydrogen-based fuels. Today, this merchant hydrogen production is complementing onsite hydrogen production in the chemicals and refining sectors. In the scenarios, the use of merchant hydrogen produced from technologies with low $CO_2$ emissions expands from very low levels today to new applications – including transport, power generation, buildings and industrial heat – contributing to $CO_2$ emission reductions in these sectors by replacing unabated fossil fuel use. This low-emissions supply is set to

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become a key part of the future energy transformation sector, alongside power generation and heat and cooling supply.

The hydrogen supply module uses a cost-optimisation framework called TIMES, a technology-rich modelling platform developed by the ETSAP TCP. The hydrogen module depicts various technology options to produce hydrogen and hydrogen-based fuels (ammonia, methanol, synthetic methane and synthetic liquid hydrocarbon fuels such as diesel and kerosene) in terms of existing capacities, conversion efficiencies, fuel costs, operating and maintenance costs, $CO_2$ emissions, $CO_2$ capture rates for fossil fuel-based technologies and capital costs for new capacity additions. Electrolyser capital costs represent a weighted average of likely deployment shares of different electrolyser technologies, with future cost reductions derived from component-wise learning curves. Capital costs for all technologies also include all balance-of-plant and engineering, procurement and construction (EPC) costs, which can represent a high share of total installed costs.

**Figure 5.2 ▷ Schematic of the hydrogen supply module**




Note: $CO_2$ = carbon dioxide; PV = photovoltaics; w/o CCS = without carbon capture and storage; w/ CCS = with carbon capture and storage.

Based on demands for merchant hydrogen and hydrogen-based fuels from the end-use sectors, the electricity and heat generation sector, refineries and biofuel production, the hydrogen supply module determines a least-cost technology mix to cover these demands. Besides these demands and the technical and economic characteristics of technologies, the module takes into account announced hydrogen production or trade projects (using the IEA's Hydrogen Production and Infrastructure Projects (IEA, 2026g) as well as policy constraints, such as $CO_2$ prices or hydrogen deployment targets).

A focus of the model analysis is on low-emissions hydrogen production, which includes hydrogen produced through water electrolysis with electricity generated from a low-emissions source (nuclear and renewables such as solar and wind). Hydrogen produced from biomass or from fossil fuels with CCUS technology is also counted as low-emissions hydrogen. Production from fossil fuels with CCUS is included only if upstream emissions are sufficiently low, if capture – at high rates – is applied to all $CO_2$ streams associated with the production route, and if all $CO_2$ is permanently stored to prevent its release into the atmosphere.[1] There are several complementary

[1] The same principle applies to low-emissions feedstocks and hydrogen-based fuels made using low-emissions hydrogen and a sustainable carbon source (of biogenic origin or directly captured from the atmosphere).

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pathways to produce low-emissions hydrogen, some of which are mature technologies and some of which are at earlier stages of development. The two dominant pathways in the GEC Model are already demonstrated at commercial scale:

- Fossil fuels with CCUS. The typical technology for producing low-emissions hydrogen from fossil fuels with CCUS is steam methane reforming (SMR) of natural gas equipped with a $CO_2$ capture unit that captures the overwhelming majority of the $CO_2$ generated by the SMR process. The hydrogen yield can be improved with the water gas shift reaction to produce $CO_2$ 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 GEC Model, cost and performance improvements are assumed to arise from higher deployment levels. The GEC Model accounts for the safe transport and permanent geological storage 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 (SOEC). The module allows the use of grid electricity for hydrogen production, which, depending on the grid electricity mix in each region, may not be a low-emissions electricity source. Dedicated renewable electricity generation from solar PV, onshore and offshore wind is modelled as a low-emissions electricity source for hydrogen production. The corresponding renewable electricity generation technologies are characterised by their cost data, capacity factors and resource potentials. The latter two are derived using geospatial analyses, characterising the renewable potential by capacity factor ranges for the model regions.

To reflect the variability of solar PV and wind for hydrogen production, the hydrogen module divides a year into four typical days, which are again divided into eight time slices of three-hour duration. Since this resolution is still too coarse to fully reflect the variability, the ETHOS model suite of Jülich Systems Analysis at Forschungszentrum Jülich, with more detailed time resolution (30 typical periods with 24 typical time slices), has been used (Forschungszentrum Jülich, 2024). The ETHOS model suite determines, for each location and its hourly solar PV, onshore and offshore wind capacity factors, the cost-optimal capacities for solar PV, wind and electrolysers as well as the need for flexibility options, such as hydrogen storage, battery storage or curtailment. This hourly analysis for a single year can take into account operational constraints of subsequent synthesis processes, such as minimum load constraints for Haber-Bosch or Fischer-Tropsch synthesis. Applying the model to a grid of raster points in a region and taking into account exclusion zones not available for electricity generation from solar PV and wind makes it possible to derive regional supply cost curves for hydrogen production. These curves are used to inform the regional potentials for hydrogen production from solar PV and wind in the GEC Model.

The production of low-emissions hydrogen-based fuels – including synthetic methane and synthetic liquid fuels such as synthetic kerosene, diesel, methanol and ammonia – becomes a key additional component of energy transformation in GEC Model 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. Ammonia can in some cases be “cracked” at the point of delivery to regenerate gaseous hydrogen. The GEC Model takes these dynamics and options into account to model the trade of gaseous hydrogen via pipelines and of liquid hydrogen, ammonia, liquid organic hydrogen carriers (LOHC) and synthetic liquid hydrocarbon fuels via ships. The energy needs and costs for the conversion processes and transport options are considered in the cost-optimisation approach of the hydrogen module.

For carbon-containing hydrogen-based fuels, the carbon input has to come from sources that are compatible with very low $CO_2$ intensity throughout the supply chain, including co-products, without offsets. In the GEC

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Model, direct air capture (DAC) and biogenic carbon captured at bioenergy conversion plants are considered as carbon sources.

The hydrogen supply module interfaces with several other modules of the GEC Model. The most notable of these is the power generation module, which is a consumer of hydrogen and hydrogen-based fuels and also provides electricity (alongside natural gas) to satisfy hydrogen production needs at lowest cost. The results of the hydrogen module for dedicated renewable electricity generation are integrated in the power generation module, and feedback across this interface is performed iteratively. Demand for hydrogen and hydrogen-based fuels in each sector is determined within each sectoral module, with iterations to update hydrogen supply costs based on overall demand where relevant. To understand the hydrogen infrastructure needs and related investment requirements, an infrastructure tool has been developed, which complements the hydrogen supply module's assessment of infrastructure needs for international hydrogen trade by analysing the domestic infrastructure needs within regions, in particular for pipelines (new or repurposed natural gas pipelines) and storage.

## 5.4 Biofuel production

Bioenergy is an important renewable energy option in all its forms: solid, liquid and gaseous (biogas and biomethane). The bioenergy supply module determines primary bioenergy availability (see Section 6.4). For liquid and gaseous uses, bioenergy is transformed in the liquid biofuels and biogas and biomethane supply modules prior to final use.

The liquid biofuels supply module builds upon previous modelling work for the WEM and ETP models and is designed to assess the deployment of liquid biofuel conversion technologies required to meet demand in the end-use sectors of transport, industry, buildings and agriculture from a variety of biomass feedstocks that are coherent with both the bioenergy supply module and the biogas and biomethane supply module. The module calculates conversion losses, energy input requirements and investment spending, and it assesses the amount of liquid biofuels production associated with CCUS.

The biogas and biomethane supply module is designed to assess the sustainable technical potential and costs of biogas and biomethane for all GEC Model 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 excluded. More information on the potential and cost assessment can be found in dedicated documentation (IEA, 2026h). The module excludes international trade of biogas and biomethane.

### *5.4.1 Liquid biofuels supply module*

Liquid biofuels today are mainly produced using commercially available technologies that convert food-based energy crops into so-called commercial biofuels. Technologies include ethanol production from starch and sugar, fatty acid methyl ester (FAME) biodiesel, and hydrotreated vegetable oil (HVO) renewable diesel. In the modelled scenarios, an increasing share of liquid biofuels is produced from emerging conversion technologies (such as biomass gasification and Fischer-Tropsch synthesis or cellulosic ethanol production) and from advanced feedstocks such as waste and residue oils, forestry residues, crop residues and non-food energy crops grown on non-arable, marginal land. Advanced feedstocks do not compete with food and feed and minimise negative environmental impacts on soil health, water resources and biodiversity.

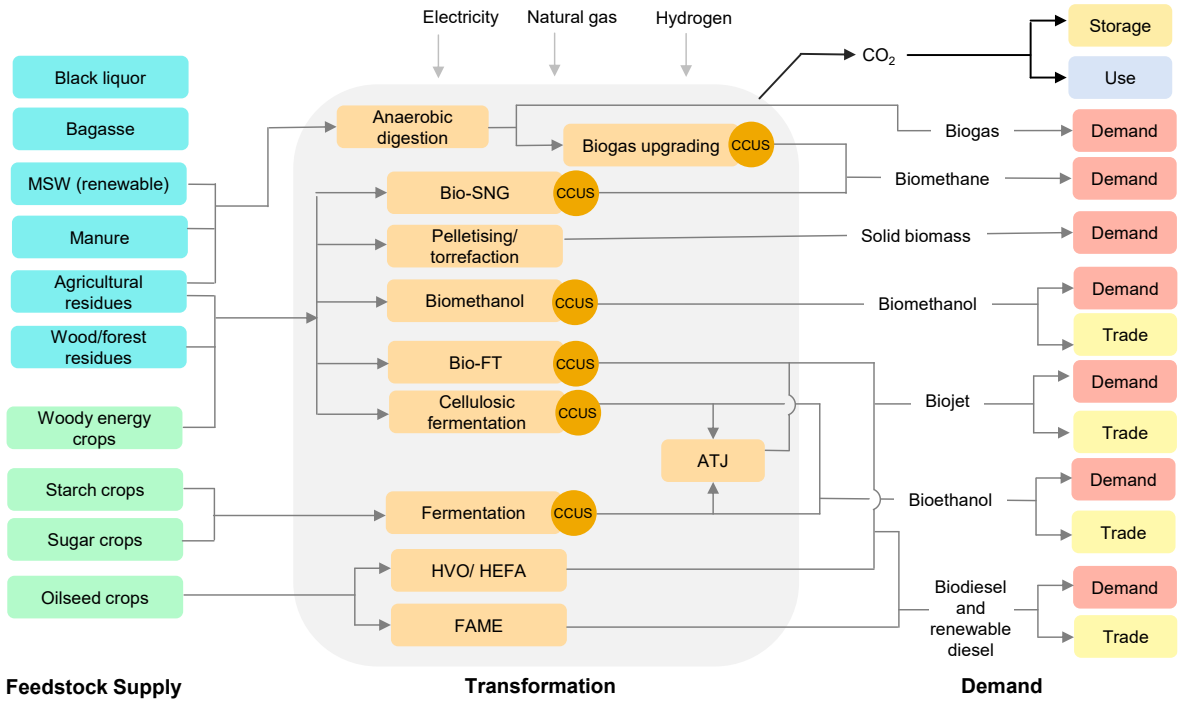
Like the hydrogen supply module, the liquid biofuels supply module is built on the TIMES modelling platform. It depicts various technology options to produce liquid biofuels (ethanol, biodiesel and renewable diesel, biojet kerosene and biomethanol) with and without carbon capture, in terms of existing capacities, conversion efficiencies, fuel and feedstock costs, operating and maintenance costs, $CO_2$ emissions, $CO_2$ capture rates and capital costs for new capacity additions. Liquid biofuel capital costs represent the latest data available from industry and academia, with future cost reductions assessed using learning curves. A variety of biomass

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feedstocks are included in the model, such as forestry residues, crop residues and non-food energy crops. These biomass feedstocks are coherent with the bioenergy supply module and the biogas and biomethane supply module. The liquid biofuels module also models liquid biofuel trade for ethanol, biodiesel and renewable diesel, biojet kerosene and biomethanol between all GEC Model regions (see Section 6.4).

Based on demand for liquid biofuels from the end-use sectors, the liquid biofuels supply module determines a least-cost technology mix to cover these demands. Besides these demands and the technical and economic characteristics of technologies, the module takes into account announced biofuel production and trade projects as assessed by the IEA's *Renewable Energy Market* reports, as well as policy constraints, such as $CO_2$ prices, biofuels subsidies or targets for emerging biofuels production.

**Figure 5.3 ▷ Schematic of liquid biofuels supply module**




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Notes: ATJ = alcohol-to-jet; CCUS = carbon capture, utilisation and storage; FAME = fatty acid methyl ester; FT = Fischer-Tropsch; HEFA = hydroprocessed esters and fatty acids; HVO = hydrotreated vegetable oil; MSW = municipal solid waste; SNG = synthetic natural gas. Bio-hydrogen production is included in the hydrogen supply module (see Section 5.3).

The liquid biofuels module includes the following conversion pathways for each liquid biofuel product:

- **Ethanol** is produced from commercial fermentation processes using starch (e.g. corn) or sugar (e.g. sugar cane) crops, or from an emerging fermentation process using cellulosic feedstocks (e.g. corn stover), in which the feedstock must first be broken down to release the sugars prior to fermentation.
- **Biodiesel and renewable diesel.**[2] Biodiesel is produced from the FAME conversion process, while renewable diesel is produced from the HVO process as well as the thermochemical process of biomass gasification followed by Fischer-Tropsch synthesis.

[2] For simplicity, both biodiesel and renewable diesel are also referred to as "biodiesel".

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- **Biojet kerosene** is produced from the HVO process (also known as hydroprocessed esters and fatty acids, or HEFA), thermochemically from biomass gasification and Fischer-Tropsch synthesis, or from commercial and emerging ethanol using the alcohol-to-jet (ATJ) pathway.
- **Biomethanol** is produced thermochemically from the biomass gasification and methanol synthesis pathway.

Additionally, several liquid biofuel production pathways can be deployed with carbon capture for use or storage. These include commercial and emerging ethanol routes, renewable diesel and biojet kerosene from biomass gasification and Fischer-Tropsch synthesis, and biomethanol from biomass gasification and methanol synthesis. Captured $CO_2$ is either stored, creating so-called carbon removals, or used to produce synthetic hydrocarbon fuels in the hydrogen module.

### *5.4.2 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, 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, 2025) 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, a by-product of ethanol production from grains, and from a World Bank study (World Bank, 2026b) 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 previously developed by the World Energy Outlook team.

Biogas is produced by anaerobic digestion. Five technologies of centralised biogas production plants are modelled: a landfill gas recovery system, a digester in a 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 GEC Model, to account for 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 was used to assess biogas and biomethane supply cost curves. For a given year, this is composed 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 into the gas grid. Supply curves are used to calculate potential GHG emissions savings and related abatement cost to understand the future role of carbon pricing in biogas and biomethane development.

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## 6.1 Oil

The purpose of this module is to project the level of oil production in each country through a bottom-up approach[1] that builds on:

- The historical time series of production by country.
- Standard production profiles and estimates of decline rates at field and country levels derived from the detailed field-by-field analysis first undertaken in the *World Energy Outlook 2008* (*WEO-2008*) and updated since.
- An extensive survey of upstream projects sanctioned, planned and announced over the short term in both Organization of the Petroleum Exporting Countries (OPEC) and non-OPEC countries, including conventional and unconventional reserves, as performed by the IEA Oil Market Report team; this is used to derive production over the projection period to 2031 (a summary of the differences in methodology between the GEC Model and the *Medium-Term Oil Market Report* when available as explained in Box 6.1).
- A methodology which aims to replicate as far as possible the decision mode of the industry in developing new reserves by using the criterion of net present value of future cash flows (Figure 6.1).
- 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.
- A comprehensive assessment of various financial risks (e.g. geopolitics, rule of law, regulatory oversight) to represent the attractiveness of investment in oil and natural gas fields.
- Values of remaining technically recoverable resources (Table 6.1) are 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 GEC Model. USGS publishes its World Petroleum Assessment, a thorough review of worldwide conventional oil and gas resources. In it, USGS divides 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 may 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 was 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 GEC Model. 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 2015 report provides its assumptions, albeit

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

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aggregated at a global level (USGS, 2015). The USGS estimate of cumulative production and reserves outside the United States is 2 060 billion barrels, 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 the GEC Model. The GEC Model estimates of remaining technically recoverable resources combine USGS undiscovered oil, USGS reserves growth and IEA estimates for known oil. Similar analysis, based on the same USGS publications, feeds into the IEA NGLs and natural gas resources database, which allows an evaluation of total conventional liquid hydrocarbons resources and conventional gas resources.

### Box 6.1 ▻ Methodological differences between the GEC Model and the annual IEA *Oil report which covers a medium-term oil markets outlook*

Nearly every year, the IEA publishes projections of oil supply and demand for the next five years in the annual Oil report and for the next two and a half decades in the World Energy Outlook, based on the GEC Model. These two sets of projections use different methodologies that evolve over time, such that comparisons are not necessarily straightforward. This box summarises the key differences.

A key difference between the annual medium term Oil report and the GEC Model is the oil price assumption. The annual medium-term Oil report assumes that the oil price follows the futures market curve at the time of publication. This is then used for demand projections, and supply is assumed to follow, with OPEC filling the gap between field-by-field projections of non-OPEC supply and demand. By contrast, the GEC Model determines the equilibrium price that brings supply and demand into balance. (This equilibrium is performed as a trend and not year by year to avoid generating investment and price cycles which would obscure policy effects and long-term trends.)

The GEC Model relies on the field-by-field analysis underlying the medium-term Oil report to guide production by country over the first five years of the projection period. The country-by-country methodology is also extended to OPEC countries, so that OPEC is not treated as the swing producer, though constraints thought to represent possible OPEC policies are incorporated in the GEC Model oil supply module.

Results are also often presented slightly differently in the two reports, including in terms of the groupings for conventional and unconventional oil. The GEC Model includes all Canadian oil sands and Venezuelan Orinoco production as unconventional oil, while the annual medium term Oil report generally counts only upgraded bitumen or extra-heavy oil as unconventional.

In analysing and projecting oil demand, the GEC Model and the medium-term Oil report have methodological differences. Since the GEC Model 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. While the GEC Model incorporates statistical differences and refinery transformation losses into historical demand values and projects those into the future, the medium-term Oil report demand definition does not include these two categories in its historical values and projections.

The GEC Model also splits biofuels from historical oil demand and projects oil demand and biofuels demand separately. The medium-term Oil report does not separate biofuels from historical oil demand, and oil demand is projected with a mix of biofuels. As a result, one barrel of oil from the annual medium term Oil report projections has lower energy content than one barrel in the GEC Model if biofuels are projected to grow. A direct comparison of GEC Model and medium-term Oil report results is thus only possible if biofuels are stripped from the medium-term Oil report oil demand values.

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

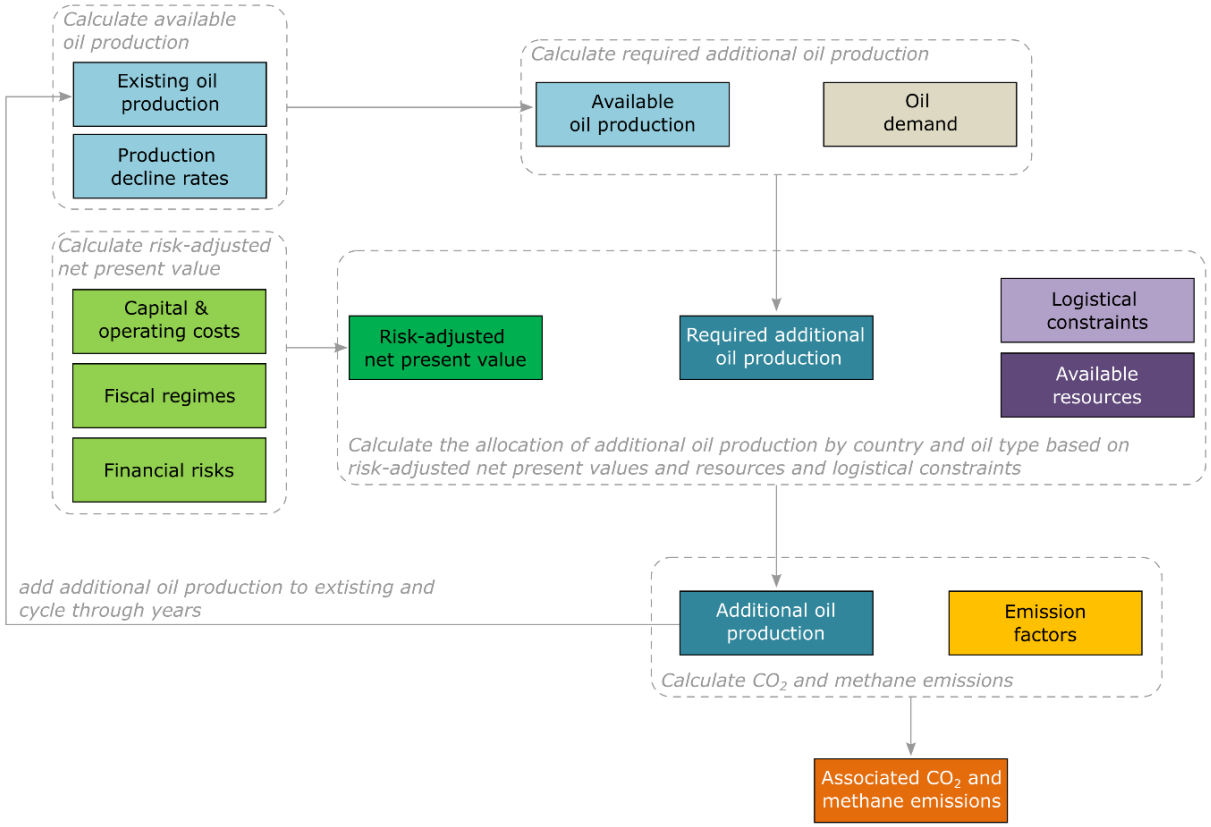
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Each country's projected oil production profile is made up of six components. Conventional crude oil fields are also distinguished by water depth (onshore, shallow [water depth less than 450 metres], deepwater [between 450 and 1 500 metres] and ultra-deepwater [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-2024: the projected decline rates in each country are derived from the analysis summarised in Box 6.1 and detailed in IEA (2025e).
- 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 NGLs.
- 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 6.1).

**Figure 6.1 ▷ Structure of the oil supply module**




In the GEC Model oil supply module, production in each country or group of countries is derived separately, according to the type of asset in which investments are made: existing fields, new fields and unconventional 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.

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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.

### 6.1.1 US tight oil model

A tight oil module is part of the GEC Model. It was originally developed for *World Energy Outlook 2016* (*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 the 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.

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 aim to drill only in their most productive areas, some wells are inevitably located in regions with lower EUR/well or higher decline rates. The product of the number of rigs, number of wells per rig and production per well then gives the new production that comes online in each play in each month starting in January. Results from this module are directly fed into the GEC Model for each of the scenarios implemented. A similar model was developed for shale gas production in the United States.

**Box 6.2 ▷ Methodology to account for production decline in oil and gas fields**

Decline rates underpin all of the IEA's scenario analyses, ranging from short to long term. The IEA has published detailed analyses on decline rates in several editions of the *World Energy Outlook (WEO),* building on the pioneering work on the topic first carried out in the *WEO-2008* and *World Energy Outlook 2009* (*WEO-2009*), as well as in the medium-term Oil report.

The work on oil and gas field decline rates was updated in 2025 (IEA, 2025e). This was based on field-by-field historical production records from the UCube database produced by Rystad Energy, an independent energy consulting services and business intelligence data firm. Rystad's UCube contains production and investment data for around 30 000 individual oil and gas assets worldwide.

Rystad compiles information from various sources, including government data, annual reports and investor presentations. The data are assigned confidence levels of high, medium, low, speculative or not available. In our analysis, we include individual oil and natural gas assets in which production has peaked only if more than 50% of the historical data points are of high confidence level or if more than 66% are of medium confidence level. Assets must also have less than 4% speculative data and no missing values. Assets based on aggregated company-level data rather than representing individual production assets were excluded, mainly in onshore areas of the United States, as were fields that have experienced prolonged disruptions due to multi-year conflicts.

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This led to a selection of around 6 500 individual post-peak oil fields and around 8 200 post-peak natural gas fields, across all regions, field types and asset sizes, as a base for this analysis. We manually reviewed all the results generated by an algorithm analysing the 1 650 largest oil fields and 1 900 largest gas fields and made adjustments to more accurately capture the post-peak decline rate profile of these fields.

This work highlighted that decline rates vary widely by field type: supergiant oil fields decline by an average of 2.7% annually, while the average for small fields is more than 11.6%. Onshore oil fields decline more slowly, by an average of 4.2% per year, than those located deep offshore at 10.3%. The Middle East, which holds the world's largest conventional onshore fields, has the lowest observed post-peak oil decline rate at 1.8%, while Europe, which has a very high share of offshore fields, exhibits the highest decline rate at 9.7%. Observed decline rates also vary over the lifetime of a field.

The decline characteristics of field types and changes in decline rates over the lifetime of a field feed directly into production profiles for resource developments within all scenarios.

## 6.2 Natural gas

Natural gas production and trade projections are derived from a hybrid GEC Model gas supply module involving bottom-up and top-down approaches. The module has similar inputs, logic and functionality to the oil supply module described above. However, unlike oil, which is assumed to be freely traded globally, gas is assumed to be primarily traded regionally, with inter-regional trade constrained by existing or planned pipelines, liquefied natural gas (LNG) plants and long-term contracts. First, the top-down module is run for 20 regions, for which indigenous production is modelled from various factors, including remaining technically recoverable resources (Table 6.1), depletion rates, production costs, taxes, prices and risks 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, and then exporting regions compete on the basis of marginal production costs plus transport costs, within current and assumed future LNG and pipeline capacities. This provides inter-regional gas trade. The effects of exporting regions' pricing policies (current or assumed for the future) can also be taken into account. Projected intra-regional trade is driven by changes in regional gas demand, considering the availability of liquefaction and regasification capacities.

In the bottom-up module, 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 from the top-down module.

## 6.3 Coal

The coal module combines a resources approach (Table 6.1) 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 composed of coking coal and steam coal, is separately modelled for the two markets and balanced on an annual basis.

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**Table 6.1 ▷ Remaining technically recoverable fossil fuel resources, 2025**

| Oil (billion barrels) | Proven reserves | Resources | Conventional crude oil | Tight oil | NGLs | EHOB | Kerogen oil |
|---|---|---|---|---|---|---|---|
| North America | 222 | 2 399 | 229 | 230 | 146 | 794 | 1 000 |
| Central and South America | 297 | 845 | 245 | 57 | 49 | 492 | 3 |
| Europe | 14 | 108 | 53 | 19 | 27 | 3 | 6 |
| Africa | 125 | 443 | 304 | 54 | 82 | 2 | - |
| Middle East | 902 | 1 127 | 849 | 29 | 205 | 14 | 30 |
| Eurasia | 146 | 935 | 223 | 85 | 57 | 552 | 18 |
| Asia Pacific | 52 | 267 | 113 | 72 | 63 | 3 | 16 |
| **World** | **1758** | **6124** | **2016** | **545** | **630** | **1860** | **1073** |

| Natural gas (trillion cubic metres) | Proven reserves | Resources | Conventional gas | Tight gas | Shale gas | Coalbed methane |
|---|---|---|---|---|---|---|
| North America | 22 | 143 | 49 | 9 | 78 | 7 |
| Central and South America | 9 | 84 | 28 | 15 | 41 | - |
| Europe | 5 | 45 | 18 | 5 | 18 | 5 |
| Africa | 19 | 100 | 50 | 10 | 40 | 0 |
| Middle East | 84 | 119 | 99 | 9 | 11 | - |
| Eurasia | 69 | 165 | 127 | 11 | 10 | 17 |
| Asia Pacific | 19 | 136 | 42 | 21 | 53 | 20 |
| **World** | **227** | **792** | **413** | **80** | **250** | **49** |

| Coal (billion tonnes) | Proven reserves | Resources | Coking coal | Steam coal | Lignite |
|---|---|---|---|---|---|
| North America | 257 | 8 387 | 1 032 | 5 836 | 1 519 |
| Central and South America | 14 | 60 | 3 | 32 | 25 |
| Europe | 137 | 978 | 165 | 413 | 400 |
| Africa | 15 | 344 | 43 | 299 | 2 |
| Middle East | 1 | 41 | 36 | 5 | - |
| Eurasia | 191 | 2 019 | 394 | 994 | 632 |
| Asia Pacific | 460 | 8 852 | 1 726 | 5 869 | 1 256 |
| **World** | **1 074** | **20 681** | **3 399** | **13 449** | **3 834** |

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

Sources: BGR (2025); CEDIGAZ (2026); Energy Institute (2026); OGJ (2025); US EIA (2026); USGS (2012a; 2012b); IEA databases and analysis.

## 6.4 Bioenergy

Bioenergy provides a significant portion of renewables-based electricity, heat and transport fuels in all scenarios of the GEC Model and – as biomethane – it can also contribute to decarbonising the gas network. Many regions or countries have or are considering policies that will further increase the demand for bioenergy in the power and transport sectors.

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The bioenergy supply module is designed to assess whether GEC Model regions can meet their demand for bioenergy for power generation, biofuels and biogases with domestic resources. Where they are not able to do so, the module also simulates the international trade of liquid biofuels. The availability of bioenergy is restricted to renewable sources of biomass feedstock that is not in competition with food and feed. The bioenergy supply module determines primary bioenergy availability, which – for liquid and gaseous uses – feeds into the liquid biofuels and biogas and biomethane supply modules for transformation prior to final use (see Section 5.4).

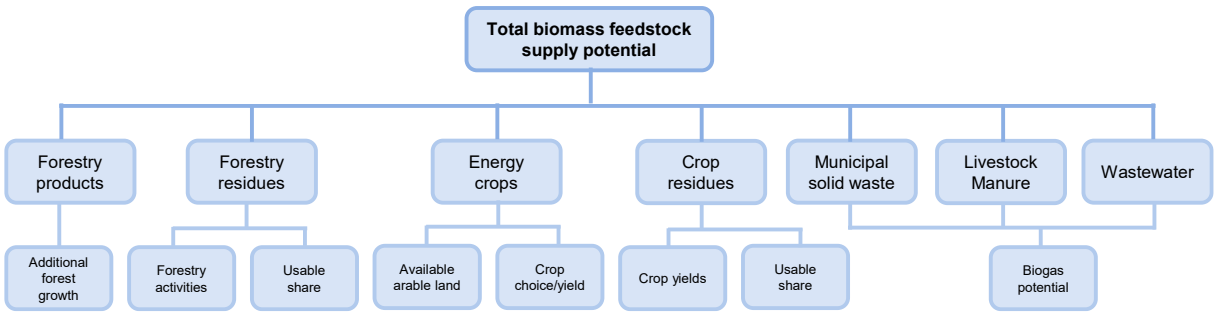
### 6.4.1 Bioenergy supply module

#### 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 FAO, as well as academic literature and the Global Agro-Ecological Zones system, a collaborative project involving FAO and 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 6.2). 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 of bioenergy.

**Figure 6.2 ▷ Schematic of biomass supply potentials**




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Note: Only the organic fraction of municipal solid waste is included in the biomass supply.

Forestry products come only from forestry activities, such as harvesting trees and complementary felling, 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 in each region, after other forestry demands are met, thereby avoiding direct deforestation.

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

Agriculture 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

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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.

Other waste and residue sources modelled are livestock manure, the organic fraction of municipal solid waste (MSW) and wastewater for biogas production. Livestock manure includes cattle, poultry, pig and sheep manure. Similarly to crop residues, these feedstock potentials are built on a wide range of data originating largely from the FAO database and OECD-FAO study (OECD-FAO, 2025) for pigs, poultry and sheep. The organic fraction of MSW includes food and green waste, paper and cardboard, and wood, and it is calculated from a World Bank study (World Bank, 2026b). Wastewater includes only municipal wastewater and is based on the output data from the water module previously developed by the World Energy Outlook team. These biomass potentials are included in the model as biogas potential.

Energy crops are those grown specifically for energy purposes, including food-crop sugar and starch feedstock for ethanol (e.g. corn, sugarcane and sugar beet), vegetable oil feedstock for bio-based diesels (e.g. rapeseed, soybean and oil palm fruit) and lignocellulosic material (e.g. switchgrass, poplar and miscanthus) for emerging 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:

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

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). Lower-quality grades of land provide lower crop yields. In this assessment, unprotected forest land is not allowed to be converted to cropland 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 emerging biofuels will increase demand for lignocellulosic energy crops, decreasing the share of land devoted to conventional feedstock.

### *Supply to meet demand*

Demand for biomass feedstock is based on demand projections for power, industry, buildings and transport sectors. To meet demand, domestic supplies are given priority; the remainder is covered through international markets for modelled bioenergy trade flows, namely liquid biofuels. The model is calibrated to match existing trade flows as assessed by the IEA's *Renewable Energy Market* reports.

### *Domestic supply*

Biomass feedstock competes to meet demand on the basis of conversion costs, including feedstock prices and energy contents. Several biomass feedstock types can be used for both power generation and the production of liquid biofuels and biogases. 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

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from the GEC Model and IEA's Mobility Model (MoMo). According to rank, available biomass feedstock supplies are allocated. Domestic supply of liquid 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 overland and by-sea costs. Four products are traded: ethanol, biodiesel, biojet kerosene and biomethanol. These liquid biofuels are high-density uniform products that can be made from residues and other feedstock. 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 liquid 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.

### *Collaboration*

IEA bioenergy demand and supply results are coupled with the Global Biosphere Management Model (GLOBIOM), developed and maintained by IIASA, to complement the IEA's analysis on bioenergy supplies and effective use strategies, particularly on biomass feedstock supply, land use and emissions from the agriculture, forestry and other land use (AFOLU) sectors.

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# Critical minerals

### *Scope*

The critical minerals model, added as a permanent module in the GEC Model during the 2022 modelling cycle, assesses the mineral requirements for the following key energy technologies:

- solar PV (utility-scale and distributed)
- wind (onshore and offshore)
- CSP (parabolic troughs and central tower)
- hydropower
- geothermal
- bioenergy for power
- nuclear power
- electricity networks (transmission, distribution and transformer)
- electric vehicles (battery electric and plug-in hybrid electric vehicles)
- battery storage (utility-scale and residential)
- hydrogen (electrolysers and fuel cells).

All of these energy technologies require metals and alloys, which are produced by processing mineral-containing ores. Ores – the raw, economically viable rocks that are mined – are beneficiated to liberate and concentrate the minerals of interest. Those minerals are further processed to extract the metals or alloys of interest. Processed metals and alloys are then used in end-use applications. While this analysis covers the entire mineral and metal value chain from mining to processing operations, we use "minerals" as a representative term for the sake of simplicity.

Our model focuses on the requirements for building a plant (or making equipment) and not on operational requirements (e.g. uranium consumption in nuclear plants).

Our model considers a wide range of minerals used in key energy technologies and listed in Table 7.1. They include chromium, copper, major battery minerals (lithium, nickel, cobalt, manganese and graphite), rare earth elements, molybdenum, platinum group metals, zinc, silicon, silver and others.

**Table 7.1 ▷ Critical minerals in scope**

| Key energy minerals | Other minerals | | | |
|---|---|---|---|---|
| • Cobalt | • Arsenic | • Hafnium | • Niobium | • Tin |
| • Copper | • Boron | • Indium | • Platinum | • Titanium |
| • Lithium | • Cadmium | • Iridium | • Selenium | • Tungsten |
| • Nickel | • Chromium | • Lead | • Silicon | • Vanadium |
| • Magnet rare earth elements (neodymium, dysprosium, praseodymium, terbium) | • Gallium | • Magnesium | • Silver | • Zinc |
| | • Germanium | • Manganese | • Tantalum | |
| • Graphite | | • Molybdenum | • Tellurium | |

Steel and aluminium are widely used across many energy technologies, but we have excluded them from the scope of this analysis. Steel does not have substantial security implications, and energy technologies are a less important driver of demand growth for steel than for critical minerals. Aluminium demand is assessed for electricity networks only, as the outlook for copper is inherently linked with aluminium use in grid lines, but is not included in the aggregate demand projections.

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In 2023, the IEA published the interactive Critical Minerals Data Explorer on its website. This online tool provides global demand projections for 37 critical minerals needed for energy transitions across the three main IEA scenarios and 12 technology-specific cases. Since 2024 and the publication of the IEA's Global Critical Minerals Outlook, the Data Explorer has also covered supply projections for the six focus minerals.

## 7.1 Demand

For each of the key energy technologies, we estimate overall mineral demand using four main variables:

- energy deployment trends under different scenarios
- sub-technology shares within each technology area based on technology-specific cases
- mineral intensity of each sub-technology
- mineral intensity improvements.

Energy deployment trends under the CPS, STEPS and NZE Scenario, as well as sub-technology shares within each technology area (e.g. solar PV module types or EV battery chemistries), are based on projections from the latest GEC modelling cycle, complemented by the *Global EV Outlook 2026* and other sources for sub-technology shares.

Mineral intensity assumptions were developed through extensive literature review and expert and industry consultations, including with IEA Technology Collaboration Programmes. The pace of mineral intensity improvements varies by scenario and technology. In areas that may particularly benefit from economies of scale or technology improvement (e.g. silicon and silver use in solar PV, platinum loading in fuel cells and use of rare earth elements in wind turbines), specific improvement rates have been applied based on the review of underlying drivers.

For the six key energy minerals, primary supply requirements have been assessed by deducting projected secondary supply (methodology below) from projected total demand. For primary supply requirements for mined materials, a certain loss ratio during refining processes is assumed.

## 7.2 Primary and secondary supply projections

### *7.2.1 Primary supply projections*

Supply projections for the key energy minerals are built using the data for the pipeline of operating and announced mining and refining projects by country. These projections are divided into a base and a high production case, with projects categorised by their probability of coming online, based on various factors such as the status of financing, permitting and feasibility studies. The base case includes production from existing assets and those under construction, along with projects that have a high chance of moving ahead as they have obtained all necessary permits, secured financing and/or established offtake contracts. The high production case additionally considers projects at a reasonably advanced stage of development, seeking financing and/or permits.

We acknowledge the use of data on mining and refining projects from various professional information sources, such as S&P Global Market Intelligence, Wood Mackenzie and Benchmark Mineral Intelligence.

### *7.2.2 Secondary supply projections*

Secondary supply includes both manufacturing scrap and end-of-life raw materials. Recycling is estimated with two parameters: the average recycling rate and the lifetime of each product in end-use sector. The recycling rate is the combination of the end-of-life collection rate (the amount of a certain product being collected for recycling) and the yield rate (the amount of material a recycling process can actually recover). The yield rate is assumed to vary according to the technically achievable yields for the extraction of each mineral using the currently available

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recycling methods. The reuse rates are much lower than the collection rate for recycling, as the use of second-life batteries (in grid applications) faces many technical and regulatory obstacles.

For the non-energy sectors, secondary mineral supply projections are based on historical trends for secondary supply in each sector, assuming gradual improvement in collection rates and efficiency levels by scenario. For energy applications, the projections have enhanced granularity by sector, with lifetime assessed by technology (for example, solar PV, wind turbines and EVs) and collection and yield rates by application and mineral, based on extensive literature review. The collection rates evolve over time and vary by scenario, with the most ambitious rates being achieved in a world that is on track for the NZE Scenario.

Lithium-ion battery recycling is modelled with the highest level of granularity among the suite of clean energy technology applications, owing to the central role these batteries play in the surge in demand for energy minerals between today and 2050. Battery recycling is modelled based on EV scrappage curves for different modes (cars, buses, two/three-wheelers and freight transport) and battery storage replacements in combination with collection rates, chemistries, recycling technology shares and process yield rates by scenario. Reuse of EV batteries in second-life applications is also accounted for. Finally, lithium-ion battery manufacturing scrap is modelled as an additional secondary source of supply.

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## 8.1 $CO_2$ emissions

As energy-related $CO_2$ emissions account for the lion's share of global GHG emissions, one of the important outputs of the GEC Model is region-by-region $CO_2$ emissions from fuel combustion and from industrial processes. Unless otherwise stated, $CO_2$ emissions reported from the GEC Model refer to combustion of fossil fuels and non-renewable waste, industrial process $CO_2$ emissions and fugitive emissions from flaring. GEC Model $CO_2$ emissions accounting also considers carbon dioxide removal from the atmosphere through capturing $CO_2$ from the air (through DAC) or from biogenic sources (bioenergy with carbon capture and storage [BECCS]) for permanent storage in underground reservoirs.

For each GEC Model 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 GEC Model regions and are assumed to remain constant over the projection period.

Process-related $CO_2$ emissions from various industrial sources are estimated by GEC Model region. 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 based on 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, ceramics, glass
- Metal industry: Primary aluminium, iron and steel
- 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 $CO_2$ removal).

The GEC Model also accounts for carbon capture, utilisation and storage (CCUS). CCUS technologies can be deployed in the electricity and heat, industry and transformation sectors. In the model, captured $CO_2$ emissions can be stored in underground geological formations, onshore or offshore, or used as a feedstock, in particular in the manufacturing of synthetic fuels.

$CO_2$ emissions from land use, land-use change and forestry (LULUCF) consistent with current policy settings (for the CPS), stated policy settings (for the STEPS), limiting the temperature rise to 1.5 °C (for the NZE Scenario), and additional responses (for the ARC), as well as bioenergy demand in IEA scenarios, have been assessed using the GLOBIOM model (IIASA, 2022).

## 8.2 Methane emissions

The Global Methane Tracker within the *GEC Model* framework is used to produce IEA estimates for methane emissions from the supply or use of fossil fuels (coal, oil and natural gas) and from the supply or use of bioenergy (such as solid bioenergy, liquid biofuels and biogases). The methodology for the main segments of methane emissions is as follows:

- **Oil and gas – Our approach to estimati**ng methane emissions from global oil and gas operations relies on generating country-specific and production type-specific emissions intensities that are applied to production and consumption data on a country-by-country basis. These intensities are based on the latest scientific

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studies and measurement campaigns as well as large emissions events detected by satellites, data on oil and gas operations, governance indicators, methane policies and regulations.

- **Coal – Estimates for coal mine** methane (CMM) emissions are derived from mine-specific emissions intensities for four major coal-producing countries. The mine-level CMM estimates generated in this way are then aggregated and verified against country-level estimates taken from satellite-based measurements. Based on these data, coal quality (e.g. the ash content or fixed carbon content of coal produced by individual mines), mine depth and regulatory oversight are used as key factors to estimate CMM emissions intensities for mines in other countries for which there are no reliable direct estimates.
- **Emissions from fuel combustion (end-use)** – Estimates for methane emissions from the use of fuels (including bioenergy) in stationary and mobile applications are from the IEA Greenhouse Gas Emissions from Energy. The Tier 1 methodology from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories has been adopted for estimating the non-$CO_2$ emissions from fuel combustion.

We also include estimates of methane emissions from abandoned coal mines and oil and gas wells. These are based on country-specific and production type-specific emissions intensities that are applied to estimates of abandoned wells and mine capacity on a country-by-country basis, assuming older facilities emit less than recently abandoned ones.

Estimates of methane emissions from biogas supply are also included and are based on an assessment of emissions from biodigesters, biogas upgrading facilities and digestate storage.

More information on the methodology used to develop estimates for methane emissions from the supply and use of energy is available in the Global Methane Tracker Documentation (IEA, 2026i).

## 8.3 Other non-$CO_2$ greenhouse gas emissions

Most energy-related GHG emissions, both $CO_2$ and non-$CO_2$, in IEA scenarios are modelled using the IEA's GEC Model. Significant sources of other climate pollutants, e.g. black carbon, are modelled by the IIASA using the GAINS model (IIASA, 2023b).

Projections for all remaining types and sources of GHG emissions, such as F-gases used mainly in industrial applications, are supplemented using the scenario database published as part of the IPCC Special Report on Global Warming of 1.5 °C (IPCC, 2018).

## 8.4 Air pollution

Emissions of major air pollutants resulting from the GEC Model energy scenarios have been estimated in co-operation with 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 fine particulate matter ($PM_{2.5}$).[1] More information can be found in the WEO Special Report on https://www.iea.org/reports/energy-and-air-pollution[2] outlining the approach, results and information about health impacts, and pollution control costs.

## 8.5 Global temperature impacts

The average global surface temperature rise that would result from GHG and aerosol emissions in GEC Model scenarios has been estimated in close co-operation with Climate Resource Pty Ltd using the *Model for the Assessment of Greenhouse Gas Induced Climate Change* (MAGICC) and drawing on other tools used by the global

[1] 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.

[2] https://www.iea.org/reports/energy-and-air-pollution

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scientific community. The MAGICC climate models have been used extensively in assessment reports written by the[3] IPCC. MAGICC7, the version used in this analysis, is featured in the IPCC's Sixth Assessment Report (IPCC, 2021) and described in Cross-Chapter Box 7.1 therein.

[3] Information sourced to Climate Resource in the *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.

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# Energy and $CO_2$ decomposition

The GEC Model includes a module – the decomposition module – used to quantify the difference in final energy consumption and $CO_2$ emissions between two scenarios or in one scenario over time. Decomposition analysis is applied ex post to all end-use sectors (industry, transport, buildings and agriculture) and the transformation sectors (electricity generation and heat production, refineries, biofuels, hydrogen and hydrogen-based fuels, and other energy sectors) in the GEC Model using the final results for the scenarios being analysed.

The difference between scenarios or points in time is apportioned to several "levers" that represent important mitigation measures to reduce energy consumption and emissions within the energy system. These include:

- **Activity:** Difference in energy or emissions from economic activity and change in service demand, e.g. increase in industrial value added, kilometres travelled or floor space used.
- **Avoided demand – resource efficiency:** Difference in energy or emissions from efficiency improvements in the use of resources, e.g. extension of building lifetimes leading to less steel or cement demand.
- **Avoided demand – behaviour:** Difference in energy or emissions from avoided demand due to behavioural shifts. Please see the behavioural change sections in Section 3 (End-use sectors) for more details.
- **Climate effect:** Difference in energy or emissions in the buildings sector caused by climate change impacts on temperature. Scenario temperature projections are used to determine the shifted energy use.
- **Energy efficiency:** Difference in energy or emissions from technical efficiency improvements of deployed technologies. Examples include improved insulation of buildings, the deployment of appliances with higher efficiency standards, improved fuel economy or more efficient motors.
- **Fuel shifts:** Difference in energy or emissions from changing the fuel used, including through using different technologies that may have higher efficiency, e.g. the shift to electric vehicles from combustion engines or the shift to heat pumps from gas boilers. This effect is further broken down into specific fuels:
    - **Electrification:** Assessing the changes for electricity, e.g. use of electric vehicles or direct electrification in industry, including efficiency gains. For emissions, this can be done in a direct decomposition (excluding emissions from the electricity and heat sector) or in an indirect decomposition (including emissions from the electricity and heat sector).
    - **Bioenergy:** Assessing the changes for bioenergy, e.g. in power generation or as a fuel in buildings, transport or industry.
    - **Other renewables:** Assessing the changes for other renewables, e.g. use of solar PV and wind for power generation or solar thermal in buildings.
    - **Hydrogen:** Assessing the changes for the use of hydrogen and hydrogen-based fuels, e.g. in the transport sector or in energy-intensive industries. Onsite hydrogen use, such as electrolytic hydrogen-based steel or ammonia production, is also allocated to this lever.
    - **Other fuel shifts:** Assessing the changes for other fuels, e.g. switches among fossil fuels or switches between fossil fuels and nuclear.
- **CCUS:** Difference in energy or emissions from the deployment of carbon capture, utilisation and storage.

The decomposition module can also apportion emission and energy changes according to technology maturity category, using the technology readiness level (TRL) of each modelled technology or strategy. The TRL assessment is based on the ETP Clean Energy Technology Guide and classifies the technologies being deployed in a given year into four tiers based on their current TRL status: mature, at market uptake, under demonstration or still a prototype. The TRL breakdown makes it possible to allocate the contribution of levers such as fuel

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switching or energy efficiency to different technological maturities, and thus to highlight where there is need for further progress in innovation to close the gap between scenarios or over time within a scenario. Only savings from behavioural measures are not allocated to a TRL since these are driven not primarily by the technologies deployed but by shifts in behaviour of end-users.

The decomposition module adheres to the Logarithmic Mean Divisia Index (LMDI) approach to break down the difference between a reference and a comparison point (either another scenario or the previous year) for a given year by the key levers (Ang, 2004). The approach is based on the Kaya equation, which singles out different effects and separates the evaluated levers. The Kaya equation can vary by sector. As an example, it can be described for $CO_2$ emissions with the activity (A) and the energy (E) for each technology (t) as follows:

$$CO_{2t} = A * \frac{A_t}{A} * \frac{E}{A_t} * \frac{CO_2}{E}$$

In this equation, individual multipliers represent the activity (A), structural changes (S), energy intensity (I) and the $CO_2$ intensity (C). These multipliers can be processed and further broken down to calculate all the above-mentioned key levers.

Applying the LMDI function to the difference between a reference (ref) and a comparison point (comp) leads to the following difference for emissions:

$$CO_{2_{t,comp}} - CO_{2_{t,ref}} = \omega_t * \left\{ \ln\left(\frac{A_{comp}}{A_{ref}}\right) + \ln\left(\frac{S_{comp}}{S_{ref}}\right) + \ln\left(\frac{I_{comp}}{I_{ref}}\right) + \ln\left(\frac{C_{comp}}{C_{ref}}\right) \right\},$$

with

$$\omega_t = \frac{CO_{2_{t,comp}} - CO_{2_{t,ref}}}{\ln CO_{2_{t,comp}} - \ln CO_{2_{t,ref}}}$$

These formulas are defined in a similar way for an energy decomposition, without the $CO_2$ intensity term. For a decomposition between scenarios, the two scenarios, comparison and reference, are the compared points, e.g. the NZE Scenario and the STEPS. For a decomposition of one scenario over time, the comparison and reference points use the same GEC Model scenario but with a delay of one year between (e.g. comparing values in "t" with values in "t-1" as a reference) to calculate the levers for each year step. For the calculation of effects in a target year, annual effects are accumulated for the period after the base year.

The decomposition module calculates the effects at high technological resolution, i.e. by end-use technology and fuel for each modelled region. This framework makes it possible to calculate interlinkages between effects, such as the indirect or direct decomposition reflecting emissions from power generation or energy efficiency improvements from fuel switching, e.g. electrification. Results at the sectoral, regional or global level are obtained by summing relevant contributions.

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## 10.1 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 GEC Model 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 spending profiles specific to each technology and country or region, overnight investment needs were distributed uniformly across construction lead times estimated for each asset, yielding 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 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 LNG projects, investment reflects the capital spending profiles typically incurred to ramp up production from a new source or to maintain output from an existing asset.

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

### *10.1.1 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. It also involves an assessment of the resulting additions to production capacity.

This analysis is based on a survey of the capital spending programmes of around 80 leading upstream oil and gas companies (national, international and pure exploration and production companies), covering actual capital spending from 2000 to 2024 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 about 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 were obtained from companies’ annual and financial reports, corporate presentations, press reports, trade publications and direct contacts in the industry.

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**Table 10.1 ▷ Sub-sectors and assets included in fuel supply investment**

| Sub-sector | Assets |
|---|---|
| Oil and gas | • Upstream oil<br>• Upstream gas<br>• Midstream oil (pipelines)<br>• Midstream gas (pipelines and LNG)<br>• Refining (greenfield)<br>• Refining (upgrade and maintenance)<br>• Flaring<br>• Upstream electrification<br>• Methane abatements |
| Coal supply | • Coal mining<br>• Coal transportation |
| Low-emissions fuels | • Biogases<br>• Liquid biofuels<br>• Hydrogen and hydrogen-based fuels production<br>• Hydrogen infrastructure |

Note: LNG = liquefied natural gas.

### *10.1.2 Long-term investment in fuel supply*

Projections of long-term investment requirements for oil, gas, coal and low-emissions fuels are generated in the respective supply-side modules. The level of investment is set to meet the 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 CCUS) and infrastructure.

### *10.1.3 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 replace or refurbish obsolete generating assets and network infrastructure. The overnight investments in generating assets are a straightforward calculation multiplying the capital cost (USD/kW) for each generating technology by the corresponding capacity additions, replacement or refurbishment for each modelled region or country. Investment outlays are then spread over time based on spending profiles that begin at the start of construction or financial close 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 GEC Model key input data page.

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For transmission and distribution networks, investment calculations include annual spending by major companies for countries with available data, covering both capacity expansions and refurbishments. For a country where company data are incomplete or missing, the full investment structure is scaled using similar country profiles and available data for that country. The applied capital costs for overnight investment are derived from past capital expenditures and data from industry surveys. Investment costs of transmission and distribution networks required for renewables integration are derived from renewable integration costs based on literature reviews.

**Table 10.2 ▷ Sub-sectors and assets included in power sector investment**

| Sub-sector | Assets |
|---|---|
| Fossil fuel-based power generation | • Coal-fired power<br>• Coal-fired power with CCUS<br>• Gas-fired power<br>• Gas-fired power with CCUS<br>• Oil-fired power<br>• Non-renewable waste |
| Nuclear power generation | • Nuclear power plants (greenfield)<br>• Refurbishments and upgrades for long-term operations |
| Renewable power generation | • Bioenergy<br>• Hydropower<br>• Wind (onshore and offshore)<br>• Geothermal<br>• Solar PV (utility-scale; residential, commercial and other distributed)<br>• Solar thermal<br>• Marine<br>• Large-scale heat pumps |
| Electricity grids | • Transmission<br>• Distribution |
| Battery storage | • Utility-scale and buildings |

Notes: CCUS = carbon capture, utilisation and storage; PV = photovoltaic.

## 10.2 Demand-side investments

Demand-side investments are typically accounted for as the incremental spending required to purchase energy-efficient end-use equipment or switch to alternative fuel end-use equipment:

- An energy efficiency investment corresponds to the incremental spending to acquire equipment that consumes less energy than would otherwise have been used to provide the service, such as lighting, heating or mobility, had the consumer not bought a more efficient option (i.e. the baseline). The additional cost of a more efficient alternative can represent a small share of the total spending on a particular energy-related good or service.
- Similarly, additional investment in decarbonisation technologies or other fuel switches is represented in end-use investment as the incremental cost compared to a baseline technology. This investment category includes the direct use of renewables, electric vehicles, electrification in buildings and industry, use of hydrogen and hydrogen-based fuels, and CCUS in industry. Changes in which investments are reduced are excluded from the calculations.

Ongoing spending is assumed to occur in the same year as assets become operational. This typically does not include all the capital value of the asset, but rather the amount that is invested (including taxes and freight costs)

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to procure new equipment compared to 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 tends to reflect either the additional amount that consumers have to pay for higher energy efficiency or another fuel or equipment over the projection period, or the incremental value of the clean energy technology compared to conventional technologies (for instance, investment in electric vehicles is estimated based on the cost premium versus ICE vehicles). While the investment analysis in the WEO focuses primarily on incremental costs, the GEC Model also calculates the total investment costs when needed to assess total investments in certain industries, end uses or technologies.

Across the GEC Model regions and for each end-use sector (industry, transport and buildings), the investment needed to move to greater efficiency levels or another fuel or equipment has 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. As much as possible, a bottom-up analysis using data on sales of goods or specific industrial processes is used. 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 additional cost for the alternative option.

**Table 10.3 ▷ Sectors, sub-sectors and assets included in end-use energy investment**

| Sector | Sub-sector |
|---|---|
| Buildings | • Energy efficiency (including building envelopes and retrofits)<br>• Electrification<br>• Renewables for end use<br>• Hydrogen-based use |
| Industry | • Energy efficiency<br>• Electrification<br>• Renewables for end use<br>• CCUS<br>• Hydrogen-based use<br>• Fossil fuel-based industrial facilities |
| Transport | • Energy efficiency<br>• Electrification<br>• Hydrogen and hydrogen-based fuels<br>• Public EV chargers |

## 10.3 Financing for investments

### *10.3.1 Sources of finance*

Investment can be classified according to five broad characteristics:

- **Accounting practice:** We distinguish between on-balance sheet finance and off-balance sheet finance. For most technologies, off-balance sheet financing corresponds to project financing, while on-balance sheet financing corresponds to corporate financing. However, we adapted this methodology for certain end-use technologies. For example, in buildings, off-balance sheet financing corresponds to retrofit, while on-balance sheet financing refers to construction.

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- **The sources of finance:** These are the ultimate suppliers of funds and are split between commercial, public, and international public finance. "Commercial finance" includes equity investments (including cash and savings) made by private enterprises and households, alongside debt from commercial banks and financial institutions. It also **accounts for** some finance from public financial institutions, such as state-owned banks, sovereign wealth funds and pension funds, although this includes a degree of state-directed lending, especially in emerging economies with strong industrial policies. "Public finance" includes public equity stakes in private corporations and state-owned enterprises, state subsidies and tax incentives, and finance from some state-owned financial institutions such as export credit agencies, as well as central banks. Finance also comes from international public financiers, including development finance institutions (DFIs), multilateral climate funds, government donors, philanthropies and export credit agencies. While these institutions may operate domestically, this category considers only their cross-border finance. Examples include Agence Française de Développement, Germany's KfW, the Japan International Cooperation Agency, the World Bank, the Asian Development Bank and philanthropic foundations. These actors deploy concessional and catalytic finance to help address risk and crowd in private capital, particularly in higher-risk markets and for emerging clean energy technologies.
- **The sources of investment:** Sources of investment are the entities that make the investment decision, usually because they are – or will become – the asset owner. Sources of finance are the entities providing the finance for this investment. We distinguish between three types of entities: public (including state-owned companies or state-owned assets), corporates and households. For example, a household that invests in rooftop solar could finance this through its own savings, borrowing from a financial institution or a public subsidy. The source of investment in all cases is the household, but the source of finance for borrowing is "commercial finance" and for subsidies is "public finance".
- **Capital structure:** Capital structure is the particular combination of debt and equity used by a company to finance itself. The debt and equity shares measured for a given sector and geography consider the capital structure of both project finance transactions and corporate balance sheets.
- **Origin of provider:** We distinguish between domestic finance and international finance.

For further details on the estimation approach, please see the *World Energy Investment 2026* Methodology Annex.

### *Cost of finance*

The GEC Model 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 NZE Scenario, 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). A detailed analysis has been conducted to reflect the costs of financing power assets, with particular attention to the evolving landscape for solar PV and wind across GEC Model countries and 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 GEC Model regions. Financing costs are expressed in pre-tax terms and calculated using the weighted average cost of capital (WACC):

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

Where:

| | |
|---|---|
| $C_e$ | Cost of equity |
| $C_d$ | Cost of debt |
| $w_i$ | share of debt or equity in the capital structure |

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For sectors in which 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 in which 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 Fisher 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 power purchase agreement (PPA) pricing.

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## 11.1 Definition of modern energy access

The GEC Model's data and projections focus on two dimensions of energy access: people having access to clean cooking solutions and to a minimum level of electricity services. The IEA defines energy access as a person living in a household with reliable and affordable access to both clean cooking facilities and sufficient electricity to provide an initial basic bundle of energy services, with the level of electricity service capable of increasing over time. This definition provides a benchmark for tracking progress towards SDG target 7.1 and forms the basis for the IEA's forward-looking analysis.

For electricity access, the minimum bundle of energy services includes several light bulbs, phone charging and a radio, corresponding to approximately 50-75 kilowatt-hours (kWh) per household per year, depending on appliance efficiency. For off-grid solar, the IEA applies a minimum capacity threshold of 10 watt-peak (Wp) for solar home systems (SHS) to be considered capable of providing this basic bundle. To account for growing electricity needs over time, the GEC Model also considers two higher levels of service: an "essential bundle" and an "extended bundle". The essential bundle includes four light bulbs operating for four hours per day, a fan for three hours and a television for two hours, equivalent to approximately 500 kWh per household per year. The extended bundle additionally includes a refrigerator and longer operating hours for lighting, television and fans, equivalent to approximately 1 250 kWh per household per year. These higher service levels are associated with larger SHS, starting at 50 Wp for the essential bundle and exceeding 100 Wp for the extended bundle.

In practice, the detailed information required to assess these levels of electricity service is not consistently available across countries. The IEA's historical electricity access database therefore relies on a simpler, binary measure of whether a household has access to the electricity grid, a mini-grid or a stand-alone system with sufficient capacity to deliver the minimum bundle of energy services. Further details on the definitions and methodology are provided in the IEA's "Guidebook for Improved Electricity Access Statistics" (IEA, 2023).

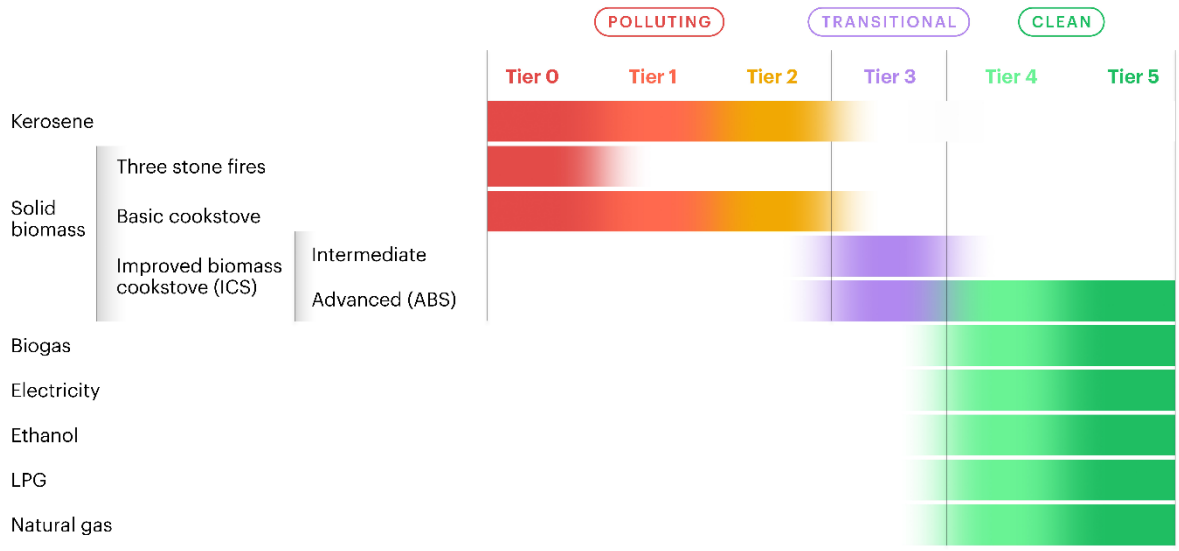
The IEA definition of clean cooking access follows the World Health Organization (WHO) definition of clean, transitional and polluting fuels and technologies, which is based on the ISO-tier framework. In this definition, a stove-fuel combination is counted as clean only if it achieves at least Tier 4 for $PM_{2.5}$ emissions and Tier 5 for carbon monoxide (CO) emissions. Tier 3 devices are treated as transitional, while those in Tiers 0-2 are classified as polluting and fall outside the scope of clean cooking access. Greenhouse gas emissions associated with a stove-fuel combination are not considered in this classification. Consequently, certain fossil fuel-based technologies, including natural gas and LPG stoves, are classified as clean cooking solutions as they meet the required indoor air pollution thresholds.

Most fuel and stove combinations are relatively straightforward, but there are nuances within solid biomass cooking. The IEA commonly distinguishes three broad types of solid biomass cooking. First is the three-stone fire, which is an open fire cooking setup in which three stones or similar supports are arranged to hold a cooking pot above the flames. Second is basic biomass stoves (ISO Tier 0-2), which are usually made of clay or metal and produced in the home or in artisanal workshops. These stoves offer only slight improvements over open fires in terms of efficiency and indoor air quality. Together, three-stone fires and basic cookstoves make up the category of traditional use of biomass (up to and including stoves of ISO Tier 2). Improved biomass cookstoves are the next tier up and are further divided into intermediate improved biomass cookstoves (ICS) and advanced biomass cookstoves, the latter being a subset of improved biomass cookstoves. ICS encompass stoves that use engineered enhancements and standardised manufacturing to improve thermal efficiency and reduce emissions. ICS include both intermediate designs (typically ISO Tier 3, considered transitional solutions) and advanced biomass cookstoves, which integrate technologies such as fans or gasifiers to achieve higher efficiency and lower emissions (ISO Tier 3-5, with the highest tiers classified as clean cooking solutions under WHO guidelines).

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A household is considered to have access to clean cooking if it cooks primarily with a clean cooking solution. These solutions include biogas, electricity, ethanol, LPG, natural gas and advanced biomass cookstoves. In practice, however, fuel stacking – the concurrent use of multiple fuel types – is widespread across emerging market and developing economies, meaning that many households classified as having clean cooking access continue to rely on traditional biomass for some cooking tasks.

**Figure 11.1 ▻ Classification of stove types by tier and access levels**




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## 11.2 Outlook for modern energy access

Different energy access pathways are explored across the WEO scenarios. In the STEPS, energy access evolves in line with current macroeconomic conditions, policies and investment trends, taking into account planned connections under existing energy access programmes. In the ARC, the pace of progress in energy access is the same as in the STEPS. In the CPS, only existing access policies and approved operations under energy access programmes are considered. The ACCESS outlines a pathway to universal modern energy access, based on the fastest historically observed rates of access expansion in comparable contexts. It achieves universal electricity access by 2035 and universal clean cooking access by 2040. The NZE Scenario follows the same pace of progress towards universal energy access as the ACCESS.

### *11.2.1 Outlook for electricity access*

The IEA's electricity access database, developed since the early 2000s by combining government data, household surveys and supply-side data, provides historical time series of electricity access rates for every country, incorporating the latest available information. Night-time satellite imagery is now used as an additional data source to monitor recent progress in electrification. Building on this database, several models have been developed to project the evolution of electricity access rates at the country level to 2050. Projections in the STEPS and CPS are based on a multivariate econometric model that relates historical country-level access rates to a range of variables, including income per capita, population growth, urbanisation rates, the fiscal environment, international financial flows, energy access policy indicators and expected outcomes of electrification programmes, such as the number of people gaining access under the World Bank's Mission 300 initiative. The methodology used to project electricity access rates in the ACCESS is described in the dedicated section below.

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To determine the technologies through which households gain electricity access in the different scenarios, the IEA uses the latest available country-level geospatial data to identify the least-cost electrification solution for each unelectrified settlement. This assessment, conducted using the publicly available OnSSET model, considers distance to the existing grid, expected electricity demand, population density and locally available energy resources. The resulting least-cost solutions are then assessed against additional factors, including the speed at which grid and off-grid systems can provide access; the potential for simultaneously electrifying other sectors such as industry, agriculture or transport; the optimal solution for maximising reliability, resilience and quality of supply; and the attractiveness of investment to different investors and vendors.

Investment requirements in electricity access are modelled on the basis of the population gaining access by technology and latest technology costs. Investments include supply infrastructure costs for the population gaining access, such as electricity generation units (for grid, mini-grids and stand-alone systems), transmission (for grids) and distribution (for grids and mini-grids) lines.

### *11.2.2 Outlook for clean cooking access*

Estimates of historical clean cooking access rates are based on the WHO Cooking Fuels and Technologies Database.[1] To provide a more up-to-date picture of recent progress, the IEA has developed an econometric approach that combines supply-side data, including cooking fuel demand and equipment trade data, with the latest information on policies and investments. This approach complements the WHO database by providing estimates for the most recent years, for which household survey data are not yet available. As with electricity access, several models have been developed to project the evolution of clean cooking access rates at the country level to 2050 across the different scenarios. In the STEPS and CPS, country-level access rates are projected using a multivariate econometric model that relates historical access rates to a range of variables, including income per capita, population growth, urbanisation rates, energy access policy and programme indicators, the fiscal environment, international financial flows, and public and private investment commitments made at the 2024 Summit on Clean Cooking in Africa. The methodology used to project clean cooking access rates in the ACCESS is described in the dedicated section below.

To determine the mix of technologies through which households gain clean cooking access across the different scenarios, the IEA uses the latest available country-level geospatial data to identify the least-cost clean cooking solutions. This assessment, conducted using the publicly available OnStove model, follows a geospatial approach similar to that used for electricity access with the OnSSET model. It considers factors such as local fuel availability, stove and fuel costs, household cooking needs and population density to identify the least-cost solutions for each area. The resulting technology mix is then assessed against additional factors, including infrastructure readiness, supply chain development and potential synergies with electrification, to reflect practical considerations for technology deployment.

Investment requirements in access to clean cooking are modelled on the basis of the population gaining access by technology and latest technology costs. Investments include end-use equipment such as stoves and biodigesters, as well as infrastructure for LPG (primary storage units, refilling and secondary storage, cylinders, and so on) and electricity (additional generation and lines to power electric cooking).

### *11.2.3 The ACCESS*

The ACCESS explores a pragmatic yet ambitious pathway for achieving universal access to modern energy in emerging market and developing economies. It examines how electricity and clean cooking access could expand by replicating the best historical rates seen in comparable contexts. The approach follows four steps applied country by country and separately for rural and urban areas:

[1] For more information, see https://www.who.int/data/gho/data/themes/air-pollution/cooking-fuel-and-technology-database-by-fuel-category

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- **Cluster rural and urban areas by country.** Rural and urban areas are first grouped into clusters using a machine-learning algorithm based on shared characteristics, including energy access levels at the start year, income, demographics, country governance and fiscal health, level of infrastructure development, and the distribution of populations across the country. These factors collectively influence the pace of achievable progress towards energy access, guided by historical best practices.
- **Project access rates based on best historical trends**. Within each cluster, the scenario applies the best-performing historical trends to model both the main transition period and the final push to reach full access. The model also considers each country's readiness to begin its transition by assessing the current state of clean cooking policies and broader governance conditions, and it accordingly estimates a "ramp-up" period of one to five years. With these factors, an S-curve is defined to project both urban and rural access rates in each country, ensuring that progress tapers as efforts shift to closing the "last-mile" gap.
- **Attribute least-cost technologies using established geospatial methods.** Technology allocation for electricity access applies the same least-cost geospatial logic as in the other scenarios, whereas for clean cooking it relies on a newly developed model within the OnStove framework, designed with a stronger focus on affordability.

  In this model, the clean cooking solution that households adopt is determined by identifying the modern cooking solution that maximises consumer benefits under a specified affordability threshold set for each country. Starting with the threshold that households spend less than 5% of their disposable income on clean cooking, the model gradually raises this level until all households can afford at least one modern clean cooking solution. This is meant to reflect the use of targeted affordability support to allow all households to gain access. At this affordability threshold, the model selects from all available modern cooking solutions that the household can afford, maximising consumer preferences and perceived benefits of convenience (time savings), health and environment. The clean cooking technology allocation process is based on current affordability, assuming today's technology costs and household income levels remain constant.

  To model affordability, household purchasing power is estimated using Meta's Relative Wealth Index combined with national income distribution curves and settlement-level household size data, yielding an average disposable income for each representative household.

  The technology shares resulting from the geospatial modelling are then combined with the S-curve adoption paths for rural and urban areas.
- **Quantify system impacts in the GEC Model.** The trajectories and technology mixes feed into the GEC Model to estimate incremental electricity and fuel demand, investment needs and associated emissions resulting from the population gaining access. Investments include generation, transmission and distribution for grid and mini-grid connections; components for stand-alone systems; and end-use equipment and supply infrastructure for clean cooking (e.g. stoves, cylinders, biodigesters, refilling and storage).

The ACCESS applies the same prevailing technology cost and fuel price assumptions as the STEPS. The ACCESS was run in 2025 but was not rerun in 2026.

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# Employment

The IEA added an energy employment module in 2020 and completed a fuller integration with the GEC Model framework and transfer to Vensim in 2022. The model provides detailed estimates of the number of people employed across the energy sector, including in resource supply, the power sector and major end-use sectors.

## 12.1 Definition and scope of employment

Employment literature typically classifies job creation impacts by the following schema:

- **Direct**: Jobs created to deliver a final project or product or operate a facility.
- **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.

Our employment analysis includes all direct jobs and the indirect jobs from suppliers that manufacture key energy-producing or energy-using technologies. Other indirect jobs, as well as induced jobs, are not included. In employment literature, indirect jobs sometimes include jobs "supported" by the purchase of equipment that 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. This sets a clear boundary around the jobs that energy investment creates to deliver new projects, or the jobs required to operate existing energy facilities.

Jobs are normalised to full-time equivalent (FTE) units for consistent accounting. One 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). For example, two separate six-month jobs are counted as one FTE job.

Employment numbers include our best estimate of the number of informal workers. In alignment with International Labour Organization (ILO) guidelines, informal employment includes all remunerative work that is not registered, regulated or protected by existing legal or regulatory frameworks (ILO, 2003). This comprises own-account workers and workers employed in informal sector enterprises; contributing family workers; employees holding informal jobs; members of informal producers' co-operatives; and own-account workers engaged in the production of goods exclusively for own final use by their household. Estimates are based on ILO data and a literature review of informality rates by region and sector.

### *Categorisation by energy technology*

Employment modelling now covers 55 energy sub-sectors for each GEC Model region under different IEA scenarios. The scope of energy employment technologies covered includes:

- The **supply** of energy and related minerals, including coal, oil and gas, modern bioenergy, critical minerals extraction and refining (lithium, copper, cobalt and nickel), nuclear fuels and low-emissions hydrogen.
- The **power sector**, including electricity generation by source (fossil fuels, renewables and nuclear) and power transmission, distribution and storage.
- Energy end-uses, including vehicle manufacturing (including four-wheelers, two/three-wheelers, parts and electric vehicle batteries) and energy efficiency (in buildings and industry).

### *Categorisation by economic activity*

Employment is categorised not only by energy technology but also by economic activity, in accordance with the International Standard Industrial Classification of All Economic Activities (ISIC), Revision 4 (UN DESA, 2008). In the employment module, the economic activities covered by the model are grouped into the following six categories:

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- **Raw materials**: Agriculture (ISIC Section A) for bioenergy production and Mining and quarrying (ISIC Section B) for production of coal, oil and gas
- **Manufacturing**: ISIC Section C
- **Construction**: ISIC Section F
- **Utilities**: Electricity, gas, steam and air conditioning supply (ISIC Section D)
- **Professionals:** Professional and business services (ISIC Sections J-N and S)
- **Wholesale and transport**: Wholesale and retail trade (ISIC Section G) and Transportation and storage (ISIC Section H)

### *Categorisation by asset life stage*

Employment is also categorised according to whether the job is associated with building a new project or operating and maintaining existing energy infrastructure. This split is based on IEA energy balances and related data. For example, the ratio between capacity additions and total installed power capacity informs the split of power sector workers between new projects and existing power plants. The term "Operations and maintenance" (O&M) is used to refer to the workers in existing energy infrastructure or assets, as an indication of all ongoing jobs required to support the proper operation of an energy project.

### *Categorisation by occupation and skill level*

Employment is also categorised by occupation and skill level, in line with the International Standard Classification of Occupations 2008 (ISCO-08) laid out by the ILO (ILO, 2025a). Occupations are defined by the ILO as a "set of jobs whose main tasks and duties are characterized by a high degree of similarity".

At the one-digit level, the ISCO-08 classification covers nine major occupational groups. As indicated in the table below, these occupational employment results are also associated with a grouped skill level, which is in turn associated with a typical minimum education level, in line with the ILO's approach to assessing educational mismatch (ILO, 2025b). These occupations, skill groups and educational requirements are outlined in Table 12.1.

**Table 12.1 ▷ Occupational groups, skill levels and typical educational requirements**

| Skill level | Occupational group (ISCO-08) | Typical minimum educational requirement (ISCED-11 level) |
|---|---|---|
| High | 1. Managers<br>2. Professionals<br>3. Technicians and associate professionals | 8. Doctoral or equivalent level<br>7. Master's or equivalent level<br>6. Bachelor's or equivalent level<br>5. Short-cycle tertiary education |
| Medium | 4. Clerical support workers<br>5. Service and sales workers<br>6. Skilled agricultural, forestry and fishery workers<br>7. Craft and related trades workers<br>8. Plant and machine operators, and assemblers | 4. Post-secondary non-tertiary education<br>3. Upper secondary education<br>2. Lower secondary education |
| Low | 9. Elementary occupations | 1. Primary education |

Notes: ISCO-08 = International Standard Classification of Occupations 2008; ISCED-11 = International Standard Classification of Education 2011. The ISCO-08 classification includes ten major occupational groups, of which nine are shown here: "0. Armed forces occupations" is not shown.

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## 12.2 Estimating current employment

Our model uses IEA energy investment and spending data, data on energy production and consumption, power capacity and electricity generation, and technology stocks and sales as the basis to estimate global employment. These data points are multiplied by employment multipliers tailored to each energy sub-sector to estimate total employment in the base year.

Multipliers are produced via a comprehensive review of labour statistics, industry and firm-level data and academic research, and by using wage data for each sub-sector and region where available. Multipliers and employment estimates have been tested with companies within the IEA's Energy Business Council, peer reviewers, academics, industry groups and international organisations such as the IMF and ILO.

### *Estimating job multipliers*

Broadly, three types of multipliers are used in the model, based on investment (jobs per million US dollars invested), volumetric data (jobs per unit produced), and facilities and capacity in operation (jobs per unit capacity). Multipliers vary by region to reflect differences in the local cost of labour and worker productivity. They also vary by energy sub-sector, reflecting different project cost breakdowns, in other words, how much of each million US dollars invested is allocated to spending on labour versus materials. The primary sources used to estimate multipliers include:

- Wage data from national statistics and international databases, for investment multipliers.
- Legal financial filings that provide information on employment, cost breakdowns for projects, firm revenues and average wages.
- Academic and intergovernmental research and modelled estimates.
- Individual company and industry group estimates.

Government surveys of businesses were prioritised, when available with sufficient detail, to support the sub-sectoral analysis. Employment and financial information was extracted from the annual reports of major companies in each sector, though this method could only be used for sectors with a high degree of consolidation in major firms that are publicly listed. Material from academic and industry sources was screened to ensure harmonised definitions, and reference values were adjusted to adhere to the framework described. Where values from these sources were unavailable, estimates were based on employment multipliers for similar technologies. Where wage data specific to energy industries is not available, generalised wage data by region is used.

### *Allocating employment throughout the project development stage*

Our employment estimates comprise both jobs in the operation of existing assets and jobs associated with the build-out of new projects. The latter are estimated based on overnight investment totals for each project. However, the totals recorded for overnight investment fall in the year of project completion, whereas jobs are generated throughout the project development phase, in the years leading up to this completion date. In our model, we therefore spread the overnight investment totals across prior years, based on typical project delivery timelines for each technology. These spread investment totals represent an estimate of the investment funds spent in each year of the project planning and construction phases. Employment in the build-out of new projects is then estimated by multiplying these investment spending estimates by the employment multipliers.

### *Calibration to available employment data*

A wide range of employment data from external sources is collected annually, to serve as benchmarks for the calibration of multipliers. These data sources include:

- National statistics for all major countries.

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- ILOSTAT databases (ILO, 2025c)
- United Nations Industrial Development Organization (UNIDO) IndStat database (UNIDO, 2025)
- Reports by international organisations and industry associations.
- Academic literature.
- Annual reports of major companies.
- Company interviews.

Where data are collected from broad labour databases, we focus on categories relevant to energy, including the complete list of ISIC codes presented in the United Nations' *International Recommendations for Energy Statistics* (UNSD, 2011). Our scope includes codes such as 0510 (mining of hard coal), 0610 (extraction of crude petroleum), 0620 (extraction of natural gas), 1920 (manufacture of refined petroleum products), 2910 (manufacture of motor vehicles), 3510 (electric power generation, transmission and distribution), 4322 (plumbing, heat and air conditioning installation), and 4930 (transport via pipeline). A mapping between ISIC and other classifications such as the North American Industry Classification System (NAICS) or the European Nomenclature of Economic Activities (NACE) enabled a harmonised approach to collecting official statistics from different countries. Data of the highest granularity available is used in each case.

#### *Allocating employment across global supply chains*

For energy technologies with highly globalised supply chains, employment estimates reflect where in the world upstream manufacturing capacity is located, rather than where the corresponding technologies are deployed. Data about the regional manufacturing capacity for specific technologies (such as solar PV panels, wind turbines and gas turbines) was sourced from internal IEA databases produced for the Energy Technology Perspectives (ETP) report, as well as other sources. The global total of manufacturing jobs was redistributed across *GEC Model* regions accordingly. For technologies that have very localised production, such as building materials and biofuels, all manufacturing jobs were assumed to be created locally.

## 12.3 Outlook for employment

Projections by scenario are based on IEA scenario results for all of the same inputs that were used to estimate base year employment. These are multiplied by the corresponding job multipliers – which are differentiated by region and energy industry – to estimate total jobs in coming years until 2035, and thereby estimate job gains and losses relative to the base year, as well as what portion of existing jobs are maintained.

#### *Estimating labour productivity improvements*

Multipliers evolve over time to reflect assumptions about labour productivity improvements. Where industry-specific historical time series of employment and corresponding production (or another relevant metric) are available, the historical rate of change is extended forward. Where specific time series are not available, data from the UN and ILO on value added and employment by economic activity are used to compute historical labour productivity improvement rates by region, which are applied to future multiplier improvements.

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# Household energy expenditures analysis

The 2022 energy crisis placed significant strain on household budgets and brought affordability issues to the fore, with the most vulnerable households and communities the hardest hit. Recognising that the success of the energy transition depends on the inclusion of these households and communities, the IEA developed a new analysis to assess household energy expenditures and the proportion of these costs relative to household income, broken down by income bracket. The analysis enables a detailed assessment of the impact of energy prices and consumption trends across income deciles, while also offering insights into how incentives are distributed.

## 13.1 Definitions and coverage

- **Household energy expenditures:** This includes the energy costs households incur for residential consumption (e.g. heating, cooling, lighting, cooking and powering appliances) as well as expenditures on fuels for private transport, such as cars and two/three-wheelers. Costs associated with public transport, including trains, buses, airplanes or ships, are not included in this analysis. Capital expenditure on end-use clean energy equipment such as EVs or heat pumps is not included in this analysis.
- **Household disposable income:** This refers to the amount of money households have available for spending and saving after deducting taxes and other mandatory payments, such as social security contributions, from their gross income. It includes income from wages, salaries, pensions, social benefits and any income from property, such as interest or dividends, minus personal taxes and contributions to social insurance schemes.
- **Disposable income decile:** In an ordered distribution of disposable income, deciles are the nine values that divide the distribution into ten equal parts. Specifically:
  - The first decile represents the income level below which 10% of households fall.
  - The fifth decile marks the median disposable income in the dataset.
  - The ninth decile represents the income level below which 90% of households fall.
- **Poorest 10%:** This refers to the first decile of the household disposable income distribution.
- **Richest 10%:** This refers to the tenth decile of the household disposable income distribution.

Expenditures related to the traditional use of biomass are excluded from this analysis, on the conservative assumption that all of this is gathered biomass that is not paid for. However, the traditional use of biomass can incur significant direct and indirect costs, including the opportunity cost of time spent gathering biomass, time that could otherwise be used for productive activities. In emerging market and developing economies, the traditional use of biomass accounts for approximately one-third of household energy demand.

This analysis takes into account government subsidies that directly affect the energy prices paid by consumers, such as energy price caps. It does not include direct payments to households, such as energy assistance checks, which have accounted for a significant portion of disposable income for low-income households in certain countries in recent years.

## 13.2 Input data

The input data for this analysis are drawn from a wide range of sources. National consumer expenditure surveys, academic publications and institutional reports are used to assess household energy consumption and expenditure by income bracket. Similar sources are used to estimate household size by income bracket in each region. Given the variety of definitions used to construct household income distributions, special attention is paid to ensuring the comparability of the collected data, with harmonisation applied where necessary.

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The dataset for household disposable income by income bracket for each GEC Model region is derived from a raw disposable income per capita dataset provided by the World Bank.

Data on energy consumption in the residential sector, road passenger light-duty vehicles, two/three-wheelers, as well as number of households, energy access, and end-user prices by fuel and sector, come from the GEC Model.

## 13.3 Methodology

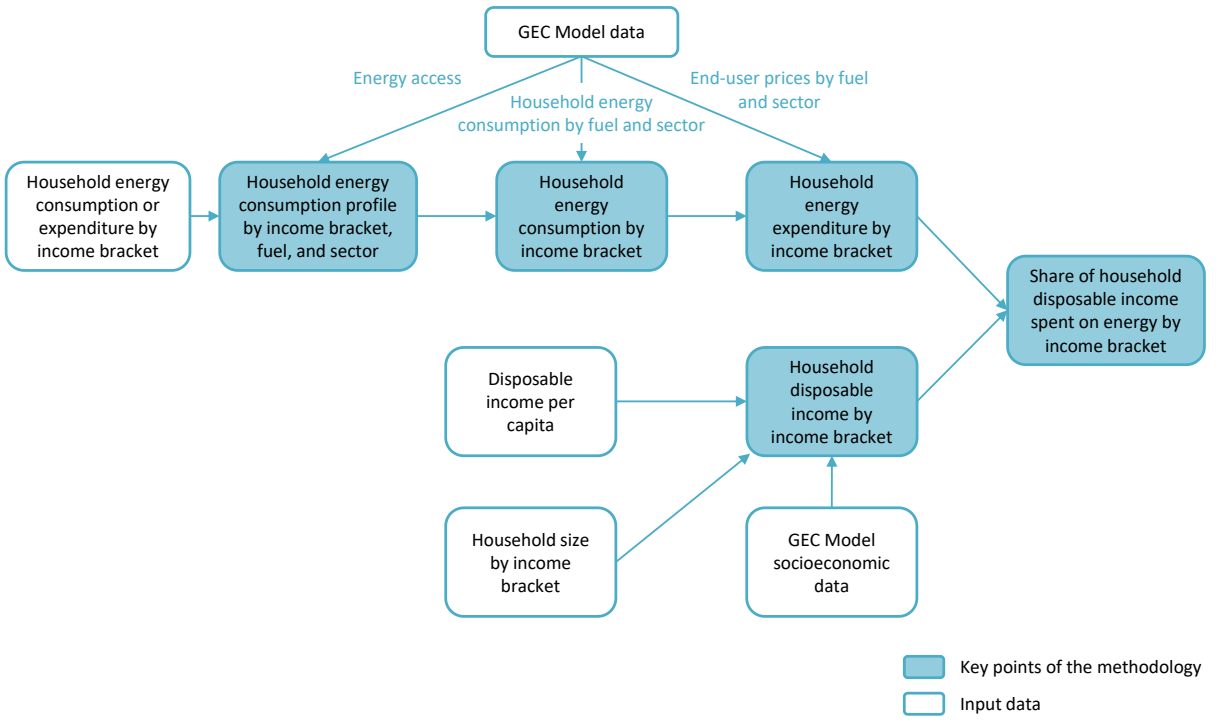
The analysis is conducted separately for each region represented in the GEC Model. These regional results are then aggregated to provide data for advanced economies and emerging market and developing economies. This methodology is applied only to historical data and is not used for projections.

National household energy consumption and expenditure data are harmonised, extrapolated and combined to develop regional energy consumption profiles by income bracket for each fuel used in the residential sector and private transport. In regions facing energy access challenges, these consumption profiles are adjusted to account for energy access data from the GEC Model, based on the assumption that those without access are in the lower income brackets. These profiles are then applied to average household energy consumption data from the GEC Model. End-user prices by fuel and sector are subsequently applied to these data, yielding energy expenditures per household by income bracket.

The raw disposable income dataset from the World Bank is integrated with socioeconomic data from the GEC Model and household size distribution data by income bracket to estimate household disposable income across GEC Model regions.

Finally, energy expenditure data and disposable income data are combined to calculate the share of household disposable income spent on energy, broken down by income bracket.

**Figure 13.1 ▷ Overview of affordability analysis methodology applied at each GEC Model region level**




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New disposable income distributions are not constructed at the aggregate level. Instead, aggregate values are calculated as the weighted average of the corresponding quantile data at the regional level, with the weights based on the number of households in each region. For instance, the energy consumption of the poorest 10% in emerging market and developing economies is the weighted average of the energy consumed by the poorest 10% in each of the countries within that group. This approach ensures that no single country is overrepresented within any income group.

## 13.4 Results

This analysis produces three primary outputs:

- energy consumption by income bracket
- energy expenditure by income bracket
- share of household disposable income spent on energy by income bracket.

Both household disposable income and energy expenditure data are benchmarked against national statistics, national surveys and other reliable sources.

In decile analysis, ten values are sometimes reported, representing either the average or median of the ten equal segments defined by the nine decile values. However, national statistics and income distribution data can vary across countries and sources, making direct comparisons difficult. To address this, all data points in this analysis are harmonised for comparability. This process, however, may introduce some uncertainties at the extremes of the dataset, particularly in the 0-10% and 90-100% ranges. To prevent these statistical artefacts from affecting the results and conclusions, only the nine decile values are presented in this analysis.

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# Terminology

This annex provides general information on terminology used throughout this report including: definitions of fuels, processes and sectors; regional and country groupings; and abbreviations and acronyms.

## Definitions

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

**Agriculture, forestry and other land use (AFOLU):** A sector included in greenhouse gas accounting frameworks which encompasses managed ecosystems. AFOLU emissions include greenhouse gas emissions from agriculture, land use, land-use change and forestry.

**Ammonia ($NH_3$):** A compound of nitrogen and hydrogen ($NH_3$) that is an industrially produced input to fertiliser manufacturing, resulting in substantial carbon dioxide ($CO_2$) emissions from the use of fossil fuel inputs to generate the input hydrogen. With properties similar to liquefied petroleum gas, ammonia can also be used directly as a fuel in direct combustion processes, as well as in fuel cells, and can be cracked to release its hydrogen content. As it can be made from low-emissions hydrogen, ammonia has the potential to be a low-emissions fuel if the production process, including nitrogen separation, is powered by low-emissions energy. Produced in such a way, ammonia is considered a low-emissions hydrogen-based liquid fuel.

**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 a main power grid may also have a source 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 hundred watts. 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, store and release electricity on demand.

**Biodiesel:** Diesel-equivalent fuel made from the transesterification of vegetable oils and animal fats, hydrogenated vegetable oil (HVO), and thermal processes such as gasification and fermentation.

**Bioenergy:** Energy content in solid, liquid and gaseous products derived from biomass feedstocks and biogas. It includes solid bioenergy, liquid biofuels and biogases. Excludes hydrogen produced from bioenergy, including via electricity from a biomass-fired plant, as well as synthetic fuels made with $CO_2$ feedstock from a biomass **source.**

**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. It includes landfill gas and sewage sludge gas, and it can be upgraded by removing non-methane constituents, principally $CO_2$.

**Biogases:** Include both biogas and biomethane.

**Biogasoline:** Includes all liquid biofuels used as a substitute for gasoline.

**Biojet kerosene:** Kerosene substitute produced from biomass. It includes conversion routes such as hydroprocessed esters and fatty acids (HEFA) and biomass gasification with Fischer-Tropsch. It excludes synthetic kerosene produced from biogenic carbon dioxide.

**Biomethane:** Biomethane is a near-pure source of methane produced either by "upgrading" biogas (a process that removes any carbon dioxide 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.

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**Buildings:** The buildings sector includes energy used in residential and services buildings. Services buildings include commercial and institutional buildings and other non-specified buildings. Building energy use includes space heating and cooling, water heating, lighting, appliances and cooking equipment. It also includes energy used by data centres and desalination plants.

**Bunkers:** Include both international marine bunker fuels and international aviation bunker fuels.

**Capacity credit:** The proportion of the nameplate generating capacity of an electrical generator that can be reliably expected to generate electricity during times of peak demand on the grid to which it is connected. The sum of all capacity credits across an electricity system is useful as an approximation of the firm power that the system can reliably provide at a given time.

**Carbon capture, utilisation and storage (CCUS):** The process of capturing carbon dioxide 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 ($CO_2$):** A gas consisting of one part carbon and two parts oxygen. It is an important greenhouse (heat-trapping) gas.

**Chemical feedstock: Physical energy products** used as raw materials to produce chemical products, typically in the petrochemicals sector. Examples are crude oil-based ethane or naphtha to produce ethylene in steam crackers.

**Clean cooking systems:** Cooking solutions that release fewer harmful pollutants and are more efficient and environmentally sustainable than traditional cooking options that make use of solid biomass, coal or kerosene. It refers to advanced biomass cookstoves, biogas/biodigester systems, electric stoves, liquefied petroleum gas, natural gas or ethanol stoves.

**Clean energy:** In *power*, clean energy includes: renewable energy sources; nuclear power; fossil fuels fitted with CCUS; hydrogen and ammonia; battery storage; and electricity grids. In *efficiency*, clean energy includes energy efficiency in buildings, industry and transport, excluding domestic navigation. In *end-use applications*, clean energy includes: direct use of renewables; electric vehicles; electrification in buildings, industry and international marine transport; CCUS in industry; and direct air capture. In *fuel supply*, clean energy includes low-emissions fuels, direct air capture and measures to reduce the emissions intensity of fossil fuel production.

**Coal:** Consists of 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 that refers to methane found in coal seams.

**Coal-to-gas (CTG):** A process by which mined coal is first turned into synthesis gas or syngas, i.e. a mixture of hydrogen and carbon monoxide, and then into synthetic methane.

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

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

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

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**Conventional natural gas:** Refers to natural gas extracted using traditional drilling techniques. It includes both onshore and offshore natural gas, including from the Arctic.

**Conventional oil:** Refers to oil extracted using traditional drilling methods. It includes onshore and offshore crude oil, including from the Arctic, enhanced oil recovery and natural gas liquids produced from conventional gas fields.

**Cooling degree days (CDDs):** A measure of cooling needs. It quantifies the difference between a reference temperature (21 °C) and daily mean outdoor temperatures on days when the latter exceed the reference temperature, summed over the year. Regional values are population-weighted to reflect the spatial distribution of the population.

**Critical minerals:** A wide range of minerals and metals that are essential for key energy, digital and other modern technologies, but whose supply chains are vulnerable to disruption. While definitions and criteria vary across countries, they typically include chromium, cobalt, copper, gallium, germanium, graphite, lithium, manganese, molybdenum, nickel, platinum group metals, zinc and rare earth elements.

**Data centres:** Facilities that house information technology (IT) equipment, such as servers, storage systems and networking equipment, and are equipped with cooling and other auxiliary systems to keep the IT equipment operating under optimal conditions.

**Decomposition analysis:** A statistical method 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 measures.

**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 capture (DAC):** A type of CCUS technology that captures $CO_2$ directly from the atmosphere using liquid solvents or solid sorbents. It is generally coupled with permanent storage of the $CO_2$ in deep geological formations or its use in the production of fuels, chemicals, building materials or other products. When coupled with permanent geological $CO_2$ storage, DAC is a carbon removal technology, and it is known as direct air capture and storage (DACS).

**Dispatchable generation:** Electricity from technologies whose power output can be readily controlled up to the nameplate capacity, i.e. increased to maximum rated capacity or decreased to zero, in order to help match supply with demand.

**Electric arc furnace:** Furnace that heats material by means of an electric arc. It is used for scrap-based steel production but also for ferroalloys, aluminium, phosphorus or calcium carbide.

**Electric vehicles (EVs):** Electric vehicles include battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs).

**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.

**Electrolysis:** Process of converting electric energy to chemical energy. Most relevant for the energy sector is water electrolysis, which splits water molecules into hydrogen and oxygen molecules. The resulting hydrogen is called electrolytic hydrogen.

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**End-use sectors:** Include industry, transport, buildings and other, i.e. agriculture and other non-energy use.

**Energy demand:** See total energy supply.

**Energy-intensive industries:** Includes production and manufacturing in the branches of iron and steel, chemicals, non-metallic minerals (including cement), non-ferrous metals (including aluminium), and paper, pulp and printing.

**Energy-related and industrial process $CO_2$ emissions:** Carbon dioxide emissions from fuel combustion, industrial processes, and fugitive and flaring $CO_2$ from fossil fuel extraction. 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 oxide ($N_2O$) emissions from the energy and industry sectors.

**Energy services:** A personal or societal gain from the use of energy. Includes, *inter alia,* heating, cooling, lighting, entertainment, mobility, nourishment, hygiene and education. Also see useful energy.

**Ethanol:** An alcohol with broad application in the chemical sector and as a fuel additive. When produced from bioresources, it is known as bioethanol, which has applications as biogasoline, a liquid fuel, and as a biochemical. In the *World Energy Outlook*, the term exclusively refers to bioethanol.

**Fischer-Tropsch synthesis:** Catalytic process to produce synthetic fuels, e.g. diesel, kerosene or naphtha, typically from mixtures of carbon monoxide and hydrogen (synthesis gas or syngas). The inputs to Fischer-Tropsch synthesis can be from biomass, coal, natural gas, or hydrogen and $CO_2$.

**Fossil fuels:** Coal, oil and natural gas. Total fossil fuel use is equal to unabated fossil fuels plus fossil fuels with CCUS and non-energy use of fossil fuels.

**Gaseous fuels:** Fuels in gaseous form, including natural gas, biogas, biomethane, hydrogen and synthetic methane.

**Gases:** See gaseous fuels.

**Gas-to-liquids (GTL):** A process by which methane reacts with oxygen or steam to produce synthesis gas or syngas, i.e. a mixture of hydrogen and carbon monoxide, followed by Fischer-Tropsch synthesis. This is similar to the process used in coal-to-liquids.

**Geothermal:** Heat derived from the sub-surface of the earth, usually using a working fluid such as water and/or steam to bring the 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 heat from ambient air and liquids). This category refers to the wide range of end-uses, including space and water heating and cooking in buildings, and desalination and process applications in industry. It does not include cooling applications.

**Heat (supply):** Obtained from the combustion of fuels, nuclear reactors, large-scale heat pumps, geothermal or solar resources. 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.

**Heating degree days (HDDs):** A measure of heating needs. It quantifies the difference between a reference temperature (16 °C) and daily mean outdoor temperatures on days when the latter fall below the reference temperature, summed over the year. Regional values are population-weighted to reflect the spatial distribution of the population.

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**Heavy-duty trucks (HDTs):** Include both medium freight trucks (gross weight 3.5 to 15 tonnes) and heavy freight trucks (gross weight >15 tonnes).

**Heavy-duty vehicles (HDVs):** Include medium freight trucks (gross weight 3.5 to 15 tonnes), heavy freight trucks (gross weight >15 tonnes) and buses.

**Heavy industries:** Iron and steel, chemicals and cement.

**Hydrogen:** Hydrogen is used in the energy system as an energy carrier or as an industrial raw material, or is combined with other inputs to produce hydrogen-based fuels. Unless otherwise stated, hydrogen in this report refers to low-emissions hydrogen.

**Hydrogen-based fuels:** Includes ammonia and synthetic hydrocarbons (gases and liquids) that derive their energy content from a pure, or nearly pure, hydrogen feedstock. If produced from low-emissions hydrogen, these fuels are low-emissions hydrogen-based fuels.

**Hydropower:** Refers to the electricity produced in hydropower projects. It excludes output from pumped storage and marine (e.g. tidal and wave technologies).

**Improved cookstoves:** Intermediate and advanced improved biomass cookstoves (ISO tier >= 3). It excludes basic improved stoves (ISO tier 0-2).

**Industry:** The sector includes fuel used within the manufacturing and construction industries. Key industry branches include iron and steel, chemicals and petrochemicals, 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 of fuels by off-road vehicles is reported under the specific sector. For instance, fuels consumed by bulldozers as a part of industrial operations are reported in industry.

**International aviation bunkers:** Include 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:** Include the 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 the capital expenditure in energy supply, infrastructure, end-use and efficiency. Fuel supply investment includes the production, transformation and transport of oil, gas, coal and low-emissions fuels. *Power sector* investment includes new construction and refurbishment of generation, electricity grids (transmission, distribution), and battery storage. *Energy efficiency* investment includes efficiency improvements in buildings, industry and transport. *Other end-use* investment includes the purchase of equipment for the direct use of renewables, electric vehicles, electrification in buildings, industry and international marine transport, equipment for the use of low-emissions fuels, and CCUS in industry and direct air capture. Data and projections reflect spending over the lifetime of projects and are presented in real terms in year-2025 US dollars converted at market exchange rates unless otherwise stated. Total investment reported for a year reflects the amount spent in that year.

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**Levelised cost of electricity (LCOE):** An indicator of the expected average production cost for each unit of electricity generated by a technology over its economic lifetime. The LCOE combines into a single metric all the cost elements directly associated with a given power technology, including construction, financing, fuel, maintenance and costs associated with a carbon price. It does not include network integration or other indirect costs. For a more complete indicator, see value-adjusted levelised cost of electricity (VALCOE).

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

**Light industries:** Include non-energy-intensive industries: food and tobacco; machinery; mining and quarrying; transport equipment; textiles; wood harvesting and processing; and construction.

**Lignite:** A 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 make long-distance transport uneconomic. In the *World Energy Outlook,* data on lignite include peat.

**Liquid biofuels:** Liquid fuels derived from biomass or waste feedstock, including ethanol, biodiesel and biojet fuels. Unless otherwise stated, biofuels are expressed in energy-equivalent volumes of gasoline, diesel and kerosene.

**Liquid fuels:** Include oil, liquid biofuels, synthetic oil products and hydrogen-based fuels, i.e. ammonia and methanol.

**Low-emissions electricity:** Includes output from renewable energy technologies, nuclear power, fossil fuels fitted with CCUS, hydrogen and ammonia.

**Low-emissions fuels:** Include modern bioenergy, low-emissions hydrogen and low-emissions hydrogen-based fuels.

**Low-emissions gases:** Include biogas, biomethane, low-emissions hydrogen and low-emissions synthetic methane.

**Low-emissions hydrogen:** Includes hydrogen that is produced through water electrolysis with electricity generated from a low-emissions source, e.g. solar, wind and nuclear power. Hydrogen produced from biomass or from fossil fuels with CCUS technology is also counted as low-emissions hydrogen. Production from fossil fuels with CCUS is included only if upstream emissions are sufficiently low, if capture at high rates is applied to all $CO_2$ streams associated with the production route, and if all $CO_2$ is permanently stored to prevent its release into the atmosphere. The same principle applies to low-emissions feedstocks and hydrogen-based fuels made using low-emissions hydrogen and a sustainable carbon source of biogenic origin or directly captured from the atmosphere.

**Low-emissions hydrogen-based fuels:** Fuels produced from low-emissions hydrogen. Include ammonia, methanol and other synthetic hydrocarbons (gases and liquids) made from low-emissions hydrogen when any carbon inputs, e.g. from $CO_2$, are not from fossil fuels or fossil-derived process emissions.

**Low-emissions hydrogen-based liquid fuels:** A subset of low-emissions hydrogen-based fuels that includes only ammonia, methanol and synthetic liquid hydrocarbons, such as synthetic kerosene.

**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.

**Marine energy:** Mechanical energy harvested from ocean currents, tidal movement or wave motion 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.

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**Modern energy access:** Applies to a person living in a household with reliable and affordable access to both electricity and clean cooking facilities. Electricity access entails sufficient supply to provide a basic bundle of energy services, equivalent to approximately 50-75 kWh per household per year, with the level of service capable of increasing over time. Clean cooking access entails the primary use of modern fuels and technologies, including LPG, natural gas, electricity and biogas, or advanced biomass cookstoves (meeting at least ISO Tier 4).

**Modern gaseous bioenergy:** See biogases.

**Modern liquid bioenergy:** Includes biogasoline, biodiesel, biojet kerosene and other liquid biofuels.

**Modern renewables:** Include all renewables with the exception of the traditional use of solid biomass.

**Modern solid bioenergy:** Includes all solid bioenergy products except the traditional use of biomass. It also includes the use of solid bioenergy in intermediate and advanced improved biomass cookstoves (ISO tier > 1), requiring fuel to be cut into small pieces or often using processed biomass such as pellets.

**Natural gas:** A gaseous fossil fuel, consisting mostly of methane. Occurs in deposits, whether liquefied or gaseous. In IEA analysis and statistics, it includes both non-associated gas originating from fields producing hydrocarbons only in gaseous form, and associated gas produced in association with crude oil production, as well as methane recovered from coal mines. Natural gas liquids, manufactured gas (i.e. produced from municipal or industrial waste, or sewage) and quantities vented or flared are not included. Natural gas has a specific energy content of 44.09 MJ/kg on a lower heating value basis. Natural 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). Natural gas data expressed in tonnes of oil equivalent, mainly to allow comparison with other fuels, are on a net calorific basis. The difference between the net and the gross calorific value is the latent heat of vaporisation of the water vapour produced during combustion of the fuel.

**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:** Gaseous fuels transported in a pipeline gas network, either separately or blended together. Include natural gas, biomethane, synthetic methane and hydrogen blended in a gas network.

**Non-energy-intensive industries:** See other industry.

**Non-energy use:** The use of energy products as raw materials for the manufacture of non-energy products, e.g. natural gas used to produce fertiliser, as well as for direct uses that do not involve using the products as a source of energy, or as a transformation input, e.g. lubrication, sealing, road surfacing, preservation or use as a solvent. Note that for biofuels, only the amounts specifically used for energy purposes, a small part of the total, are included in energy statistics. Therefore, the non-energy use of biomass is not taken into consideration and the quantities are null by definition.

**Non-renewable waste:** Non-biogenic waste, such as plastics in municipal or industrial waste.

**Nuclear power:** Refers to the electricity produced by a nuclear reactor, assuming an average conversion efficiency of 33%.

**Off-grid systems:** Mini-grids and stand-alone systems for individual households or groups of consumers not connected to a main grid.

**Offshore wind:** Refers to electricity produced by wind turbines that are installed in open water, usually in the ocean. Includes fixed offshore wind (fixed to the seabed) and floating offshore wind.

**Oil:** A liquid fuel. Usually refers to fossil fuel mineral oil. Includes oil from both conventional and unconventional oil production. Petroleum products include refinery gas, ethane, liquefied petroleum gas, aviation gasoline,

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motor gasoline, jet fuel, 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 energy losses in converting primary energy into a form that can be used in the final consuming sectors. It includes losses in low-emissions hydrogen and hydrogen-based fuels production, bioenergy processing, 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 is not accounted for in the other energy sector category.

**Other industry:** A category of industry branches that includes construction, food processing, machinery, mining, textiles, transport equipment, wood processing and remaining industry. It is sometimes referred to as non-energy-intensive industry.

**Passenger car:** 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.

**Peat:** A solid formed from the partial decomposition of dead vegetation under conditions of high humidity and limited air access, i.e. the initial stage of coalification. It is available in two forms for use as a fuel, sod peat and milled peat. Peat used for non-energy purposes is not included.

**Plastic collection rate:** Proportion of plastic that is collected for recycling relative to the quantity of recyclable waste available.

**Plastic waste:** Refers to all post-consumer plastic waste with a lifespan of more than one year.

**Power generation:** Refers to electricity generation and heat production from all sources of electricity, including electricity-only power plants, heat plants, and co-generation, i.e. combined heat and power plants. Both main activity producer plants and small plants that produce electricity or heat for their own use, i.e. auto-producers, are included.

**Primary chemicals:** Include ethylene, propylene, benzene, toluene, mixed xylenes, ammonia and methanol.

**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.

**Process heat:** The use of thermal energy to produce, treat or alter manufactured goods.

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

**Rare earth elements (REEs):** A group of 17 chemical elements in the periodic table, specifically the 15 lanthanides plus scandium and yttrium. REEs are vital inputs for key energy technologies, including wind turbines, electric vehicle motors and electrolysers.

**Renewables:** Include bioenergy, geothermal, hydropower, solar photovoltaics, concentrating solar power, wind and marine (tidal 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:** This refers to all road vehicle types, i.e. passenger cars, two/three-wheelers, light commercial vehicles, buses and medium and heavy freight trucks.

**Self-sufficiency:** Corresponds to indigenous production divided by total energy supply.

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**Services:** A component of the buildings sector. It represents energy used in commercial facilities, e.g. offices, shops, hotels, restaurants, and in institutional buildings such as schools, hospitals and public offices. Energy use in services includes space heating and cooling, water heating, lighting, appliances, cooking, data centres and desalination.

**Shale gas:** A type of unconventional natural gas contained within a commonly occurring rock classified as shale. Shale formations are characterised by low permeability, with more limited ability for gas to flow through the rock than within a conventional reservoir. Shale gas is generally produced using hydraulic fracturing. See also tight oil.

**Shipping/navigation:** This transport mode 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 (starting and ending 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.

**Single-use plastics (or disposable plastics):** Plastic items used only one time before disposal.

**Solar:** Includes solar photovoltaics (PV), concentrating solar power (CSP), and solar heating and cooling.

**Solar home systems (SHS):** Small-scale photovoltaic and battery stand-alone systems, i.e. with capacity higher than or equal to 10 watt peak (Wp), supplying electricity for single households or small businesses. They are most often used off-grid, but also where grid supply is not reliable.

**Solar photovoltaics (PV):** Electricity produced from solar photovoltaic cells, including utility-scale and small-scale installations.

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

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

**Stand-alone systems:** Small-scale autonomous electricity supply for households or small businesses. They are generally used off-grid, but also where grid supply is not reliable. Stand-alone systems include solar home systems, small wind or hydro generators and diesel or gasoline generators. The difference compared with mini-grids is in scale and in that stand-alone systems do not have a distribution network serving multiple customers.

**Steam coal:** A 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:** Methane from sources other than natural gas, including coal-to-gas and low-emissions synthetic methane.

**Synthetic oil:** Liquid fuels obtained via a process other than the refining of crude oil or bituminous oils. Synthetic oil is produced through Fischer-Tropsch conversion or methanol synthesis. It includes oil products from coal-to-liquids, gas-to-liquids and non-ammonia low-emissions liquid hydrogen-based fuels.

**Tight oil:** A type of unconventional oil produced from shale or other very low-permeability formations, generally using hydraulic fracturing. It is sometimes referred to as light tight oil. Tight oil includes tight crude oil and condensate production except for the United States, where it 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 equivalent to electricity and heat generation plus the other energy sector, excluding electricity, heat and hydrogen, plus total final consumption, excluding electricity, heat and hydrogen. TES does not include ambient heat from heat pumps or electricity trade.

**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,

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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 they are 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 (SDG). It incorporates total final consumption by end-use sectors, but it 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 SDG 7.2.1), in which TFEC is the denominator.

**Traditional use of biomass:** Refers to the use of solid biomass with basic technologies, such as a three-stone fire or basic improved cookstoves (ISO tier 0-2), often with no or poorly operating chimneys. Forms of biomass used include wood, wood waste, charcoal, agricultural residues and other bio-sourced fuels such as animal dung.

**Transport:** Includes 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. Energy consumption from 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 <3.5 tonnes); medium freight trucks (gross vehicle weight 3.5-15 tonnes); and heavy freight trucks (gross vehicle weight >15 tonnes).

**Unabated fossil fuel use:** Fossil fuels used for energy purposes without carbon capture, utilisation and storage (CCUS). Total fossil fuel use is equal to unabated fossil fuels plus fossil fuels with CCUS plus non-energy use of fossil fuels.

**Unconventional natural gas:** Includes tight gas, shale gas, coalbed methane, gas hydrates and coal-to-gas products.

**Unconventional oil:** Includes mining and in-situ extra-heavy oil and bitumen, synthetic crudes made by upgrading bituminous (e.g. oil sands in Canada) or extra-heavy crude oils, light tight oil, kerogen oil, coal-to-liquids (CTL) and gas-to-liquids (GTL) products, additives and natural gas liquids from unconventional natural gas fields.

**Useful energy:** Energy available to end-users to satisfy their need for energy services. As a 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. See energy services.

**Value-adjusted levelised cost of electricity (VALCOE):** A more complete metric to evaluate the competitiveness of power generation technologies. It includes all direct technology costs (LCOE) combined with the estimated value of three services provided to the system: energy, flexibility and capacity.

**Variable renewable energy (VRE):** Sources of renewable energy, usually electricity, for which the maximum output of an installation at a given time depends on the availability of fluctuating environmental inputs. 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 building (ZCRB):** A building where both the thermal envelope and technical building systems are highly energy efficient. Orientation and glazing are optimised, and all the essential passive elements of the thermal envelope are highly energy efficient to manage heat transfer and solar gains, ensuring the necessary comfort of occupants in all seasons. In major heating markets, when hydronic systems are used, the heating distribution system is prepared for low-temperature heat flow. In major cooling markets, zero-carbon-ready buildings are designed to optimise natural ventilation and make use of shading and reflective or green roofs to

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minimise heat gains. Heating and cooling service demand of new zero-carbon-ready buildings is below 40 kWh/m2/year, except for high-latitude regions and tropical regions with exceedingly high levels of humidity. Existing buildings can reach such a level of performance if retrofitted to ensure that technical building systems and all the essential passive elements of the thermal envelope are highly energy efficient, that shading and reflective or green roofs are used to minimise heat gains, and that the heating distribution system is prepared for low-temperature heat flow.

**Zero-carbon building (ZCB):** A building where both the thermal envelope and technical building systems are highly energy efficient, which uses either renewable energy directly or an energy supply that can be fully decarbonised, such as electricity or district heat.

**Zero emissions vehicles (ZEVs):** Vehicles capable of operating without tailpipe $CO_2$ emissions, i.e. battery electric, plug-in hybrid and fuel cell vehicles.

## Regional and country groupings

Results from the *GEC Model* are often presented with the regional groupings below:

**Advanced economies:** Organisation for Economic Co-operation and Development (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, The 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), Bolivarian Republic of Venezuela (Venezuela), Brazil, Chile, Colombia, Costa Rica, Cuba, Curaçao, Dominican Republic, Ecuador, El Salvador, Guatemala, Guyana, Haiti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, Uruguay 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, Gibraltar, Iceland, Israel[5], Kosovo[6], Montenegro, North Macedonia, Norway, Republic of Moldova, Serbia, Switzerland, Türkiye, Ukraine and United Kingdom.

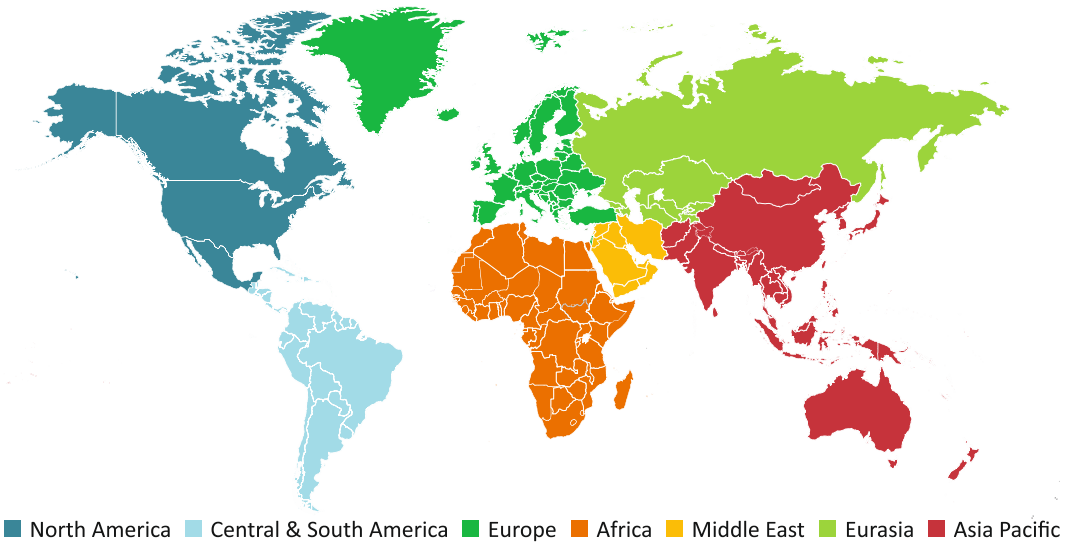
**European Union:** Austria, Belgium, Bulgaria, Croatia, Cyprus[1,2], Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain and Sweden.

**IEA (International Energy Agency):** Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea, Latvia, Lithuania, Luxembourg, Mexico, New Zealand, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Netherlands, Türkiye, United Kingdom and United States.

**Latin America and the Caribbean (LAC):** Central and South America regional grouping and Mexico.

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**Figure A.1 ▷ Main country 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.

**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):** IEA grouping plus Chile, Colombia, Costa Rica, Iceland, Israel, and Slovenia.

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

**OPEC+:** OPEC grouping plus Azerbaijan, Bahrain, Brunei Darussalam, Kazakhstan, Malaysia, Mexico, Oman, Russian Federation, South Sudan and Sudan.

**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). Timor-Leste joined ASEAN on 26 October 2025 and is excluded from this *WEO* grouping for this publication, but it is included in aggregate within the overarching Asia Pacific group.

**Sub-Saharan Africa:** Angola, Benin, Botswana, Cameroon, Côte d'Ivoire, Democratic Republic of the Congo (DRC), Equatorial Guinea, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Kingdom of Eswatini, Madagascar, Mauritius, Mozambique, Namibia, Niger, Nigeria, Republic of the Congo (Congo), Rwanda, Senegal, South Africa, South Sudan, Sudan, United Republic of Tanzania (Tanzania), Togo, Uganda, Zambia, Zimbabwe and other African countries and territories.[7]

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### *Country notes*

[1] Note by Republic of Türkiye: 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. Türkiye recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Türkiye 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 Türkiye. 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, 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, Sint Eustatius and Saba, British Virgin Islands, Cayman Islands, Dominica, Falkland Islands (Malvinas), Grenada, Montserrat, Saint Kitts and Nevis, Saint Lucia, Saint Pierre and Miquelon, Saint Vincent and the Grenadines, Saint Maarten (Dutch part) and 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] This designation is without prejudice to positions on status, and is in line with United Nations Security Council Resolution 1244/99 and the Advisory Opinion of the International Court of Justice on Kosovo's declaration of independence.

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

## *Fossil fuel supply regions*

As noted in the model description, the fossil fuel supply modules have a different regional breakdown from that used in the rest of the GEC Model. This allows the supply modules to more accurately capture the particularities of fossil fuel producing countries and regions. The regional breakdown for these modules is as follows:

### *Oil and natural gas supply module regions*

The *GEC Model* oil and natural gas supply module consists of 113 regions, of which 102 countries are modelled on an individual basis. Trade volumes broken down 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 Europe, Other developing economies in Europe, North Africa, West Africa, East Africa, Russia, Caspian, Middle East, Japan and Korea, Australia and New Zealand, 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 as follows:

**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 Europe:** Greenland, Israel, Norway and the United Kingdom.

**Other developing economies in Europe:** Ukraine.

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

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**West Africa:** Angola, Benin, Cameroon, Central African Republic, Chad, Congo, Democratic Republic of the 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 Kuwait and Saudi Arabia include 50% each of production from the Neutral Zone.

**Japan and Korea:** Japan and Korea.

**Australia and New Zealand:** 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.

### *Coal supply module regions*

In the GEC Model coal supply module, 21 countries are modelled on an individual basis: Argentina, Australia, Brazil, Canada, Chile, China, Colombia, Costa Rica, India, Indonesia, Japan, Korea, Mexico, Mongolia, Mozambique, New Zealand, Russia, South Africa, the United States, Venezuela and Viet Nam.

## Abbreviations and acronyms

| | |
|---|---|
| **AC** | air conditioner (buildings) |
| **AC** | alternating current (electricity) |
| **ACCESS** | Accelerating Clean Cooking and Electricity Services Scenario |
| **ACEA** | European Automobile Manufacturers' Association |
| **AFOLU** | agriculture, forestry and other land use |
| **AIM** | Aviation Integrated Model |
| **APEC** | Asia-Pacific Economic Cooperation |
| **APS** | Announced Pledges Scenario |
| **ARC** | Additional Response Case |
| **ASEAN** | Association of Southeast Asian Nations |
| **ASIF** | activity, structure, intensity and fuel use |
| **ATJ** | alcohol-to-jet |
| **BECCS** | bioenergy equipped with CCUS |
| **BEV** | battery electric vehicle |
| **CAAGR** | compound average annual growth rate |
| **CAFE** | corporate average fuel economy standards |
| **CAPEX** | capital expenditure |
| **CBM** | coalbed methane |
| **CCGT** | combined-cycle gas turbine |
| **CCUS** | carbon capture, utilisation and storage |
| **CDR** | carbon dioxide removal |

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| | |
|---|---|
| **CEM** | Clean Energy Ministerial |
| **$CH_4$** | 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** | coefficient of performance |
| **CPS** | Current Policies Scenario |
| **CSP** | concentrating solar power |
| **CTG** | coal-to-gas |
| **CTL** | coal-to-liquids |
| **DAC** | direct air capture |
| **DACS** | direct air capture and storage |
| **DACU** | direct air capture and utilisation |
| **DC** | direct current |
| **DER** | distributed energy resources |
| **DFI** | development finance institutions |
| **DRI** | direct reduced iron |
| **DSI** | demand-side integration |
| **DSO** | distribution system operator |
| **DSR** | demand-side response |
| **EAF** | electric arc furnace |
| **EHOB** | extra-heavy oil and bitumen |
| **EMDE** | emerging market and developing economies |
| **EOR** | enhanced oil recovery |
| **EPA** | Environmental Protection Agency (United States) |
| **EPC** | engineering, procurement and construction |
| **ESG** | environmental, social and governance |
| **ETP** | Energy Technology Perspectives |
| **ETS** | emissions trading system |
| **ETSAP** | Energy Technology Systems Analysis Program |
| **EU** | European Union |
| **EU ETS** | European Union Emissions Trading System |
| **EV** | electric vehicle |
| **EVSE** | electric vehicle supply equipment |
| **FAME** | fatty acid methyl ester |
| **FAO** | Food and Agriculture Organization of the United Nations |
| **FCEV** | fuel cell electric vehicle |
| **FDI** | foreign direct investment |
| **FID** | final investment decision |
| **FiT** | feed-in tariff |
| **FOB** | free on board |
| **FTE** | full-time equivalent |
| **GAINS** | Greenhouse Gas – Air Pollution Interactions and Synergies |
| **GDP** | gross domestic product |
| **GEC Model** | Global Energy and Climate Model |

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| | |
|---|---|
| **GHG** | greenhouse gases |
| **GIMF Model** | Global Integrated Monetary and Fiscal Model |
| **GIS** | geographic information system |
| **GLOBIOM** | Global Biosphere Management Model |
| **GTL** | gas-to-liquids |
| **$H_2$** | hydrogen |
| **HDV** | heavy-duty vehicle |
| **HEFA** | hydrogenated esters and fatty acids |
| **HFO** | heavy fuel oil |
| **HRS** | hydrogen refuelling stations |
| **HSR** | high-speed rail |
| **HVDC** | high-voltage direct current |
| **HVO** | hydrotreated vegetable oil |
| **IAEA** | International Atomic Energy Agency |
| **ICE** | internal combustion engine |
| **ICS** | improved biomass cookstoves |
| **IEA** | International Energy Agency |
| **IGCC** | integrated gasification combined cycle |
| **IIASA** | International Institute for Applied Systems Analysis |
| **ILO** | International Labour Organization |
| **IMF** | International Monetary Fund |
| **IMO** | International Maritime Organization |
| **IOC** | international oil company |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **IPT** | independent power transmission |
| **IRENA** | International Renewable Energy Agency |
| **ISCED** | International Standard Classification of Education |
| **ISCO** | International Standard Classification of Occupations |
| **ISIC** | International Standard Industrial Classification |
| **ISO** | International Organization for Standardization |
| **IT** | information technology |
| **JRC** | Joint Research Centre |
| **LCOE** | levelised cost of electricity |
| **LCV** | light commercial vehicle |
| **LDV** | light-duty vehicle |
| **LED** | light-emitting diode |
| **LHC** | Low Hormuz Case |
| **LMDI** | Logarithmic Mean Divisia Index |
| **LNG** | liquefied natural gas |
| **LOHC** | liquid organic hydrogen carrier |
| **LPG** | liquefied petroleum gas |
| **LRMC** | long-run marginal cost |
| **LULUCF** | land use, land-use change and forestry |
| **MAGICC** | Model for the Assessment of Greenhouse Gas Induced Climate Change |
| **MEPS** | minimum energy performance standards |
| **MER** | market exchange rate |
| **MoMo** | Mobility Model |

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|---|---|
| **$N_2O$** | nitrous oxide |
| **NACE** | European Nomenclature of Economic Activities |
| **NAICS** | North American Industry Classification System |
| **NDC** | Nationally Determined Contribution |
| **NEA** | Nuclear Energy Agency (an agency within the OECD) |
| **NGLs** | natural gas liquids |
| **NGV** | natural gas vehicle |
| **$NH_3$** | ammonia |
| **NOC** | national oil company |
| **$NO_X$** | nitrogen oxides |
| **NPV** | net present value |
| **NZE** | Net Zero Emissions by 2050 Scenario |
| **O&M** | operations and maintenance |
| **OECD** | Organisation for Economic Co-operation and Development |
| **OnSSET** | Open Source Spatial Electrification Tool |
| **OPEC** | Organization of the Petroleum Exporting Countries |
| **OPEX** | operational expenditure |
| **PEM** | polymer electrolyte membrane or proton exchange membrane |
| **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 |
| **SAF** | sustainable aviation fuel |
| **SDG** | Sustainable Development Goals (United Nations) |
| **SHS** | solar home systems |
| **SME** | small and medium enterprises |
| **SMR** | steam methane reforming |
| **$SO_2$** | sulphur dioxide |
| **SOEC** | solid oxide electrolyser cells |
| **STEPS** | Stated Policies Scenario |
| **SUVs** | sport utility vehicles |
| **SVO** | straight vegetable oil |
| **T&D** | transmission and distribution |
| **TCP** | Technology Collaboration Programme |
| **TES** | total energy supply |
| **TFC** | total final consumption |
| **TFEC** | total final energy consumption |
| **TIMES Model** | The Integrated MARKAL-EFOM System Model |
| **TPED** | total primary energy demand |
| **TRL** | technology readiness level |
| **TSO** | transmission system operator |
| **UAE** | United Arab Emirates |

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| | |
|---|---|
| **UCL** | University College London |
| **UN** | United Nations |
| **UNDP** | United Nations Development Programme |
| **UNEP** | United Nations Environment Programme |
| **UNFCCC** | United Nations Framework Convention on Climate Change |
| **UNIDO** | United Nations Industrial Development Organization |
| **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 |
| **ZCB** | zero-carbon building |
| **ZCRB** | zero-carbon-ready building |
| **ZEV** | zero emissions vehicle |

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# References


Aboumahboub et al. (2010), Optimal Configuration of a Renewable-based Electricity Supply Sector, https://www.researchgate.net/publication/228870612_Optimal_Configuration_of_a_Renewable-based_Electricity_Supply_Sector

Air Transport Systems Lab (2026), Aviation Integrated Model, https://www.atslab.org/our-models.html

Ang, B. W. (2004), Decomposition analysis for policymaking in energy: which is the preferred method? Energy Policy Volume 32, Issue 9, June 2004, 1131-1139, https://www.sciencedirect.com/science/article/pii/S0301421503000764

BGR (Bundesanstalt für Geowissenschaften und Rohstoffe) (2025), BGR Energy Study 2025 - Data and Developments Concerning German and Global Energy Supplies (Summary), https://www.bgr.bund.de/DE/Themen/Rohstoffe/Downloads/Downloads_EN/Energiestudien/energiestudie_2025.html

BNEF (Bloomberg New Energy Finance) (2025), Energy Storage System Cost Survey 2025, https://bnef.com/insights/38229

Brockway, P. E. (2024), A country-level primary-final-useful (CL-PFU) energy and exergy database: overview of its construction and 1971–2020 world-level efficiency results. Environmental Research Energy, https://iopscience.iop.org/article/10.1088/2753-3751/ad4e39

CBS (2025), Data centres consume 4.6 percent of the Netherlands' electricity, https://www.cbs.nl/en-gb/news/2025/51/data-centres-consume-4-6-percent-of-the-netherlands-electricity

CEDIGAZ (2026), Cedigaz databases, https://www.cedigaz.org/databases/

CEPII (2026), BACI: International Trade Database at the Product-Level, https://www.cepii.fr/CEPII/en/bdd_modele/bdd_modele_item.asp?id=37

Change Energy Services and Pollution Probe (2021), Passenger Vehicle Greenhouse Gas Emissions Reduction Technology Review, https://www.pollutionprobe.org/ghg-emissions-reduction-tech-review/

CSO (2026), Data Centres Metered Electricity Consumption 2025, https://www.cso.ie/en/releasesandpublications/ep/p-dcmec/datacentresmeteredelectricityconsumption2025/

Dargay, J., D. Gately and M. Sommer (2007), Vehicle Ownership and Income Growth, Worldwide: 1960-2030. The Energy Journal, 28(4), https://doi.org/10.5547/ISSN0195-6574-EJ-Vol28-No4-7

DCCEEW (2025), Data Centres and Energy Implications, https://www.dcceew.gov.au/sites/default/files/documents/81616.pdf

DRCSC (2024), 韩雪：数据中心的低碳运营有效缓解 AI 巨大能耗需求 [Low-carbon operation of data centers effectively alleviates the huge energy consumption demand of AI], https://www.drc.gov.cn/DocView.aspx?chnid=379&leafid=1338&docid=2907711

ECMWF (European Centre for Medium-Range Weather Forecasts) (2026), ECMWF Reanalysis v5 (database), https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5

EEA (European Environment Agency) (2025), Monitoring of $CO_2$ emissions from passenger cars Regulation (EU) 2019/631 (database), https://www.eea.europa.eu/en/datahub/datahubitem-view/fa8b1229-3db6-495d-b18e-9c9b3267c02b

EIA (2026), Assumptions to the Annual Energy Outlook 2026: Oil and Gas Supply Module, https://www.eia.gov/outlooks/aeo/assumptions/


IEA. CC BY 4.0.

EIA (2025), 2022 MECS Survey Data (database). U.S Energy Information Administration, https://www.eia.gov/consumption/manufacturing/data/2022/

Energy Institute (2026), Statistical Review of World Energy, https://www.energyinst.org/statistical-review

ENTSO-E (European Network of Transmission System Operators for Electricity) (2014), Transparency Platform (database), https://transparency.entsoe.eu/

EPA (2024a), Fuel Economy Data (database), https://www.fueleconomy.gov/

EPA (2024b), The 2024 EPA Automotive Trends Report, https://www.epa.gov/automotive-trends/download-2024-automotive-trends-report

European Commission (2024a), Commission report under Article 12(3) of Regulation (EU) 2019/631 on the evolution of the real-world $CO_2$ emissions gap for passenger cars and light commercial vehicles, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52024DC0122

European Commission (2023), Commission Regulation (EU) 2017/1151 (consolidated version of 1 September 2023), https://eur-lex.europa.eu/eli/reg/2017/1151/2023-09-01/eng

Financial Times (2020), Electric car costs to remain higher than traditional engines, https://www.ft.com/content/a7e58ce7-4fab-424a-b1fa-f833ce948cb7

Forbes (2021), In 2020 HDD Companies Shipped Over 1ZB of Storage Capacity, https://www.forbes.com/sites/tomcoughlin/2021/02/07/in-2020-hdd-companies-shipped-over-1zb-of-storage-capacity/

Forschungszentrum Jülich (2024), ETHOS Model Suite, https://www.fz-juelich.de/en/ice/ice-2/expertise/model-services

Gartner (2020), Gartner Says Worldwide Server Revenue Grew 5.1% in the Fourth Quarter of 2019, While Shipments Increased 11.7%, https://www.gartner.com/en/newsroom/press-releases/2020-03-19-gartner-says-worldwide-server-revenue-grew-5-percent-in-the-fourth-quarter-of-2019-while-shipments-increased-11-percent

Gartner (2018a), Gartner Says Worldwide Server Revenue Grew 25.7 Percent in the Fourth Quarter of 2017, While Shipments Increased 8.8 Percent, https://www.gartner.com/en/newsroom/press-releases/2018-03-08-gartner-says-worldwide-server-revenue-grew-in-the-fourth-quarter-of-2017

Gartner (2018b), Gartner Says Worldwide Server Revenue Grew 33.4 Percent in the First Quarter of 2018, While Shipments Increased 17.3 Percent, https://www.gartner.com/en/newsroom/press-releases/2018-06-11-gartner-says-worldwide-server-revenue-grew-33-percent-in-the-first-quarter-of-2018-while-shipments-increased-17-percent

Gartner (2017a), Gartner Says Worldwide Server Revenue Grew 16 Percent in the Third Quarter of 2017; Shipments Grew 5.1 Percent, https://www.gartner.com/en/newsroom/press-releases/2017-12-11-gartner-says-worldwide-server-revenue-grew-16-percent-in-third-quarter-of-2017

Gartner (2017b), Gartner Says Worldwide Server Shipments Declined 4.2 Percent in the First Quarter of 2017; Revenue Declined 4.5 Percent, https://www.gartner.com/en/newsroom/press-releases/2017-06-07-gartner-says-worldwide-server-shipments-declined-4-percent-in-the-first-quarter-of-2017-revenue-declined-4-percent

Gartner (2016a), Gartner Says Worldwide Server Revenue Declined 0.8 Percent in the Second Quarter of 2016, While Shipments Increased 2 Percent, https://www.gartner.com/en/newsroom/press-releases/2016-09-14-gartner-says-worldwide-server-revenue-declined-1-percent-in-the-second-quarter-of-2016-while-shipments-increased-2-percent

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Gartner (2016b), Gartner Says Worldwide Server Revenue Grew 8.2 Percent in the Fourth Quarter of 2015, While Shipments Increased 9.2 Percent, https://www.gartner.com/en/newsroom/press-releases/2016-03-09-gartner-says-worldwide-server-revenue-grew-8-percent-in-the-fourth-quarter-of-2015-while-shipments-increased-9-percent

Gartner (2015a), Gartner Says Worldwide Server Market Grew 4.8 Percent in Shipments, While Revenue Increased 2.2 Percent in Fourth Quarter of 2014, https://www.gartner.com/en/newsroom/press-releases/2015-03-03-gartner-says-worldwide-server-market-grew-4-percent-in-shipments-while-revenue-increased-2-percent-in-fourth-quarter-of-2014

Gartner (2015b), Gartner Says Worldwide Server Revenue Grew 7.5 Percent in the Third Quarter of 2015, While Shipments Increased 9.2 Percent, https://www.gartner.com/en/newsroom/press-releases/2015-12-02-gartner-says-worldwide-server-revenue-grew-7-percent-in-the-third-quarter-of-2015-while-shipments-increased-9-percent

Gartner (2015c), Gartner Says Worldwide Server Shipment Market Grew 8 Percent in the Second Quarter of 2015, While Revenue Increased 7.2 Percent, https://www.gartner.com/en/newsroom/press-releases/2015-08-26-gartner-says-worldwide-server-shipment-market-grew-8-percent-in-the-second-quarter-of-2015-while-revenue-increased-7-percent

Gartner (2015d), Gartner Says Worldwide Server Shipments Grew 13 Percent in the First Quarter of 2015, While Revenue Increased 17.9 Percent, https://www.gartner.com/en/newsroom/press-releases/2015-05-28-gartner-says-worldwide-server-shipments-grew-13-percent-in-the-first-quarter-of-2015-while-revenue-increased-18-percent

Gartner (2014a), Gartner Says Worldwide Server Shipments Grew 1 Percent in the Third Quarter of 2014 While Revenue Increased 1.7 Percent, https://www.gartner.com/en/newsroom/press-releases/2014-12-03-gartner-says-worldwide-server-shipments-grew-1-percent-in-the-third-quarter-of-2014-while-revenue-increased-1-percent

Gartner (2014b), Gartner Says Worldwide Server Shipments Market Grew 1.3 Percent in the Second Quarter of 2014 While Revenue Increased 2.8 Percent, https://www.gartner.com/en/newsroom/press-releases/2014-08-27-gartner-says-worldwide-server-shipments-market-grew-1-percent-in-the-second-quarter-of-2014-while-revenue-increased-2-percent

Gartner (2014c), Gartner Says Worldwide Server Shipments Market Grew 1.4 Percent in the First Quarter of 2014, While Revenue Declined 4.1 Percent, https://www.gartner.com/en/newsroom/press-releases/2014-05-28-gartner-says-worldwide-server-shipments-market-grew-1-percent-in-the-first-quarter-of-2014-while-revenue-declined-4-percent

GEM (Global Energy Monitor) (2026), Global Oil and Gas Plant Tracker (database), https://globalenergymonitor.org/projects/global-oil-plant-tracker

Global Fuel Economy Initiative (2021), GFEI Working Paper 22 - Vehicle fuel economy in major markets 2005-2019, https://www.globalfueleconomy.org/resources/gfei-working-paper-22

Google (2025), Efficiency. Google DataCenters, https://datacenters.google/efficiency/

Gouveia, J. P., P. Fortes and J. Seixas (2012), Projections of energy services demand for residential buildings: Insights from a bottom-up methodology. 47, 430-442, https://www.sciencedirect.com/science/article/pii/S0360544212007207

GWI (2026), DesalData, https://www.desaldata.com/

Heide, D. et al. (2010), Seasonal optimal mix of wind and solar power in a future, highly renewable Europe. Renewable Energy, 35(11), 2483-2489, https://www.sciencedirect.com/science/article/pii/S0960148110001291

IEA. CC BY 4.0.

Hintemann, R., S. Hinterholtzer and F. Konrat (2024), Server Stock Data — A Basis for Determining the Energy and Resource Requirements of Data Centres. 2024 Electronics Goes Green 2024+ (EGG), 1-5, https://ieeexplore.ieee.org/abstract/document/10631194

Hofmann, F. et al. (2021), atlite: A Lightweight Python Package for Calculating Renewable Power Potentials and Time Series. Journal of Open Source Software, 6(62), 3294, https://doi.org/10.21105/joss.03294

IAEA (International Atomic Energy Agency) (2026), Power Reactor Information System (PRIS) (database), https://pris.iaea.org/

IATA (International Air Transport Association) (2026), Air Passenger Market Analysis, https://www.iata.org/en/publications/economics/

IATA (2007), Estimating Air Travel Demand Elasticities, https://www.iata.org/en/iata-repository/publications/economic-reports/estimating-air-travel-demand-elasticities---by-intervistas/

ICAO (2010-2024), Presentation of Air Transport Statistical Results, https://www.icao.int/about-icao/AnnualReport2024/world-air-transport-2024

ICCT (2024), On the way to 'real-world' $CO_2$ values? The European passenger car market after 5 years of WLTP, https://theicct.org/wp-content/uploads/2024/01/ID-76-%E2%80%93-EU-WLTP_final.pdf

ICCT (2023), Real-world performance of battery electric passenger cars in China: Energy consumption, range, and charging patterns, https://theicct.org/wp-content/uploads/2023/04/Passenger-cars-BEVs-real-world_final.pdf

ICCT (2021a), Methods of converting the type-approval fuel economy and $CO_2$ emission values of light vehicles: An analysis for New Zealand, https://theicct.org/publication/methods-of-converting-the-type-approval-fuel-economy-and-co2-emission-values-of-light-vehicles-an-analysis-for-new-zealand/

ICCT (2021b), Evaluation of real-world fuel consumption of light-duty vehicles in China: A 2021 update, https://doi.org/https://doi.org/10.1016/j.apenergy.2023.121353

ICCT (2014), Development of Test Cycle Conversion Factors among Worldwide Light-Duty Vehicle $CO_2$ Emission Standards, https://theicct.org/publication/development-of-test-cycle-conversion-factors-among-worldwide-light-duty-vehicle-co2-emission-standards/

IDC (2024), Datacenter Trends: Sustainable Builds and Carbon Emissions, https://www.idc.com/getdoc.jsp?containerId=IDC_P33186

IEA (International Energy Agency) (2026), Interactive map of global biogas and biomethane potential, https://www.iea.org/data-and-statistics/data-tools/interactive-map-of-global-biogas-and-biomethane-potential

IEA (2026a), Data and statistics (database), https://www.iea.org/data-and-statistics

IEA (2026b), Global Energy Review 2026, https://www.iea.org/reports/global-energy-review-2026

IEA (2026c), World Energy Investment 2026, https://www.iea.org/reports/world-energy-investment-2026

IEA (2026d), Global Hydrogen Review 2026, https://www.iea.org/reports/global-hydrogen-review-2026

IEA (2026e), Global EV Outlook 2026, https://www.iea.org/reports/global-ev-outlook-2026

IEA (2026f), Global Energy and Climate Model key input data (database), https://www.iea.org/data-and-statistics/data-product/global-energy-and-climate-model-key-input-data

IEA (2026g), Hydrogen Production and Infrastructure Projects Databases, https://www.iea.org/data-and-statistics/data-product/hydrogen-production-and-infrastructure-projects-database

IEA. CC BY 4.0.

IEA (2026h), Global Methane Tracker Documentation, 2026 Version, https://www.iea.org/reports/global-methane-tracker-2026

IEA (2025a), Fossil Fuel Subsidies, https://www.iea.org/topics/fossil-fuel-subsidies

IEA (2025b), Electric Vehicles Initiative, https://www.iea.org/programmes/clean-energy-ministerial/electric-vehicles-initiative

IEA (2025c), World Energy Balances Documentation, https://www.iea.org/data-and-statistics/data-product/world-energy-balances#documentation

IEA (2025d), Cost of Capital Observatory. International Energy Agency, https://www.iea.org/reports/cost-of-capital-observatory

IEA (2025e), The Implications of Oil and Gas Field Decline Rates, https://www.iea.org/reports/the-implications-of-oil-and-gas-field-decline-rates

IEA (2024a), Energy Technology Perspectives, https://www.iea.org/reports/energy-technology-perspectives-2024

IEA (2024b), Real-Time Electricity Tracker (database). Data and Statistics, https://www.iea.org/data-and-statistics/data-tools/real-time-electricity-tracker

IEA (2024c), Weather for Energy Tracker (database). Data and statistics, https://www.iea.org/data-and-statistics/data-tools/weather-for-energy-tracker

IEA (2023), Guidebook for Improved Electricity Access Statistics, https://www.iea.org/reports/guidebook-for-improved-electricity-access-statistics

IEA (2019), Material efficiency in clean energy transitions, https://www.iea.org/reports/material-efficiency-in-clean-energy-transitions

IEA-ETSAP (IEA Energy Technology Systems Analysis Programme) (2026), TIMES, https://iea-etsap.org/index.php/etsap-tools/model-generators/times

IIASA (International Institute for Applied Systems Analysis) (2023a), Primary, Final and Useful Energy Database (PFUDB), https://iiasa.ac.at/models-tools-data/pfudb

IIASA (2023b), GAINS Technical Reports. IIASA, https://gains.iiasa.ac.at/models/gains_tech_reports.html

IIASA (2022), Global Biosphere Management Model. IIASA, https://iiasa.ac.at/models-tools-data/globiom

ILO (International Labour Organization) (2025a), International Standard Classification of Occupations (ISCO), https://ilostat.ilo.org/methods/concepts-and-definitions/classification-occupation/

ILO (2025b), Education and Mismatch Indicators (database), https://ilostat.ilo.org/databases/emi/description/

ILO (2025c), ILOSTAT (database), https://ilostat.ilo.org/data

ILO (2003), Guidelines concerning a statistical definition of informal employment. ILO, https://www.ilo.org/resource/guidelines-concerning-statistical-definition-informal-employment-0

IMF (International Monetary Fund) (2026), World Economic Outlook: October 2026 Edition, https://www.imf.org/en/publications/weo/issues/2026/10/13/world-economic-outlook-october-2026

IMO (2025), Report on annual carbon intensity and efficiency of the fleet (Reporting year: 2024), https://www.imo.org/en/ourwork/environment/pages/data-collection-system.aspx

IPCC (Intergovernmental Panel on Climate Change) (2021), IPCC Sixth Assessment Report, https://www.ipcc.ch/report/ar6/wg1/

IEA. CC BY 4.0.

IPCC (2018), Global Warming of 1.5 °C, https://www.ipcc.ch/sr15/

IRENA (International Renewable Energy Agency) (2026), Renewable Power Generation Costs in 2025. International Renewable Energy Agency, https://www.irena.org/Publications/2026/Jul/Renewable-Power-Generation-Costs-in-2025

IUCN (2008), Guidelines for Applying Protected Area Management Categories, https://portals.iucn.org/library/node/9243

JATO (2021), Electric Vehicles: A Pricing Challenge 2021, https://info.jato.com/electric-vehicles-a-pricing-challenge

Jerrelind, J. et al. (2021), Contributions of vehicle dynamics to the energy efficient operation of road and rail vehicles, https://www.tandfonline.com/doi/full/10.1080/00423114.2021.1913194#d1e192

JRC (2017), Light Duty Vehicle $CO_2$ Emission Reduction Cost Curves and Cost Assessment - the DIONE Model. Publications Office of the European Union, https://publications.jrc.ec.europa.eu/repository/handle/JRC108725

JRC (2018a), Li-ion Batteries for Mobility and Stationary Storage Applications, https://publications.jrc.ec.europa.eu/repository/handle/JRC113360

JRC (2018b), Heavy duty vehicle $CO_2$ emission reduction cost curves and cost assessment — Enhancement of the DIONE model. Publications Office of the European Union, https://publications.jrc.ec.europa.eu/repository/handle/JRC112013

JRC (2023), Calculating heavy-duty vehicle $CO_2$ emission reduction costs for Green Deal scenarios: Extension of the DIONE model. Elsevier BV, https://publications.jrc.ec.europa.eu/repository/handle/JRC127497

Kamiya, G. and V. C. Coroamă (2025), Data Centre Energy Use: Critical Review of Models and Results. 4E EDNA, https://www.iea-4e.org/edna/publications/data-centre-energy-use-critical-review-of-models-and-results/

KEA (2025), 2025 vehicle efficiency analysis report, https://www.energy.or.kr/energy_issue/mail_vol269/pdf/2025_KEA_02.pdf

Koomey, J. (2011), Growth in data center electricity use 2005 to 2010. A report by Analytical Press, completed at the request of The New York Times, https://alejandrobarros.com/wp-content/uploads/old/Growth_in_Data_Center_Electricity_use_2005_to_2010.pdf

Koplow, D. (2009), Measuring Energy Subsidies Using the Price-Gap Approach: What does it leave out? IISD, https://www.iisd.org/publications/report/measuring-energy-subsidies-using-price-gap-approach-what-does-it-leave-out

KTH Royal Institute of Technology (2014), OpeN Source Spatial Electrification Toolkit (ONSSET), https://www.energy.kth.se/energy-systems/completed-projects/open-source-spatial-electrification-toolkit-onsset-1.940024

LEAP (2026), Useful Energy Demand Analysis, https://leap.sei.org/Help24/Demand/Useful_Energy_Analysis.htm

Lei, N. and E. Masanet (2022), Climate- and technology-specific PUE and WUE estimations for U.S. data centers using a hybrid statistical and thermodynamics-based approach, https://www.sciencedirect.com/science/article/pii/S0921344922001719

Maeil Business (2024), The concentration of data centers in the metropolitan area, which consumes a lot of power, has intensified, https://www.mk.co.kr/en/economy/11031490

Malmodin, J. et al. (2024), ICT sector electricity consumption and greenhouse gas emissions – 2020 outcome. Telecommunications Policy, 48(3), 102701, https://doi.org/10.1016/j.telpol.2023.102701

IEA. CC BY 4.0.

Masanet, E. et al. (2020), Recalibrating global data center energy-use estimates. Science, 367(6481), 984-986, https://www.science.org/doi/abs/10.1126/science.aba3758

MIIT (2024), Fuel consumption interactive table (database). China, Ministry of Industry and Information Technology, https://yhgscx.miit.gov.cn/fuel-consumption-web/mainPage

Mousavi, B. (2019), Analysis of the relative roles of supply-side and demand-side measures in tackling global climate change : application of a hybrid energy system model. Univesity of Stuttgart, https://elib.uni-stuttgart.de/items/acb6b39f-8a19-4747-a198-43885e1c284c

National Grid (2025), Data Centre Impact Study, https://dso.nationalgrid.co.uk/resource-centre/publications-library

NREL (National Renewable Energy Laboratory) (2021), Cost Projections for Utility-Scale Battery Storage: 2021 Update, https://research-hub.nlr.gov/en/publications/cost-projections-for-utility-scale-battery-storage-2021-update/

NREL (2011), Eastern Wind Integration and Transmission Study. National Renewable Energy Laboratory, https://www.nrel.gov/docs/fy11osti/47078.pdf

NREL (2010a), Western Wind and Solar Integration Study. National Renewable Energy Laboratory, https://www.nlr.gov/grid/wwsis

NREL (2010b), National Solar Radiation Database (database). National Renewable Energy Laboratory, https://nsrdb.nrel.gov/

OAG (2026), OAG (database), https://www.oag.com/airline-schedules-data

OECD (Organisation for Economic Co-operation and Development) (2026), Historical population data (database), https://www.oecd.org/en/data.html

OECD-FAO (2025), OECDFAO Agricultural Outlook 20252034, https://www.oecd.org/en/publications/2025/07/oecd-fao-agricultural-outlook-2025-2034_3eb15914.html

OGJ (2025), OGJ survey reveals increase in global oil & gas gas reserves, https://www.ogj.com/general-interest/economics-markets/article/14302481/global-oil-and-natural-gas-reserves-both-increase

Olsen, D. et al. (2013), Grid Integration of Aggregated Demand Response, Part I : Load Availability Profiles and Constraints for the Wester Interconnection. Ernest Orlando Lawrence Berkeley National Laboratory, https://eta-publications.lbl.gov/publications/grid-integration-aggregated-demand

OMDIA (2026a), Data Center Compute Intelligence Service, https://omdia.tech.informa.com/advance-your-business/cloud-and-data-center/data-center-compute-intelligence-service

OMDIA (2026b), Data Center Capacity and Investment Intelligence Service, https://omdia.tech.informa.com/advance-your-business/cloud-and-data-center/data-center-capacity-and-investment-intelligence-service

Oxford Economics (2026), Global Economic Databank: October 2026 Update (database), https://www.oxfordeconomics.com

Oxford Economics (2024), Tradeprism (database), https://www.oxfordeconomics.com/subscriptions/tradeprism/

Paoli, L. and J. Cullen (2023), Technical limits for energy conversion efficiency. Energy, 192, https://www.repository.cam.ac.uk/items/d2ed05c3-ded0-4d65-abe0-bbbadba725d1

Priesmann, J. et al. (2021), Time series of useful energy consumption patterns for energy system modeling. 8, 148, https://pmc.ncbi.nlm.nih.gov/articles/PMC8166825/

IEA. CC BY 4.0.

S&P Global (2026), S&P Capital IQ Pro (database), https://www.spglobal.com/market-intelligence/en/solutions/products/sp-capital-iq-pro

S&P Global Mobility (2024), Global New Vehicle Registrations (database), https://www.marketplace.spglobal.com/en/datasets/global-new-vehicle-registrations-(248)

Saint-Drenan, Y. M. (2020), A parametric model for wind turbine power curves incorporating environmental conditions, https://www.sciencedirect.com/science/article/pii/S0960148120306613

Semianalysis (2025), Custom Market Intelligence, https://semianalysis.com/

Shehabi, A. et al. (2024), 2024 United States Data Center Energy Usage Report. Lawrence Berkeley National Laboratory, https://escholarship.org/uc/item/32d6m0d1

Shehabi, A. et al. (2018), Data center growth in the United States: decoupling the demand for services from electricity use. Environmental Research Letters, https://iopscience.iop.org/article/10.1088/1748-9326/aaec9c

Singapore, Ministry of Digital Development and Information (2021), MCI response to PQ on data on total carbon emissions by data centres in Singapore, https://www.mddi.gov.sg/newsroom/mci-response-pq-data-carbon-emissions-data-centres-sg/

SPEC (2024), SPECpower_ssj 2008 (database), https://www.spec.org/power_ssj2008/results/

Statista (2024), Data Center - Worldwide (database), https://www.statista.com/outlook/tmo/data-center/worldwide

Technical University of Denmark (2016), Ship-Desmo, https://danishshipping.dk/en/policy/climate/ship-design-calculation-tool/

Ueckerdt, F. et al. (2013), System LCOE: What are the costs of variable renewables? Energy, 63, 61-75, https://www.sciencedirect.com/science/article/pii/S0360544213009390

UN DESA (United Nations Department of Economic and Social Affairs) (2025), World Urbanization Prospects (database), https://population.un.org/wup/

UN DESA (2024), World Population Prospects 2024 (database), https://population.un.org/wpp/

UN DESA (2008), International Standard Industrial Classification of All Economic Activities Revision 4, https://unstats.un.org/unsd/classifications/Econ/isic

UNCTAD (United Nations Conference on Trade and Development) (2025), Review of Maritime Transport 2025. United Nations Publications, https://unctad.org/publication/review-maritime-transport-2025

UNIDO (United Nations Industrial Development Organization) (2025), Industrial Statistics Database (INDSTAT), https://stat.unido.org/data/table

United Nations (2025), UN Global Platform - AIS Data, https://unstats.un.org/bigdata/task-teams/ais/index.cshtml

UNSD (United Nations Statistics Division) (2011), International Recommendations for Energy Statistics, https://unstats.un.org/unsd/energystats/methodology/ires/

USGS (United States Geological Survey) (2015), U.S. Geological Survey assessment of reserve growth outside of the United States. USGS (United States Geological Survey), https://doi.org/10.3133/sir20155091

USGS (2012a), An Estimate of Undiscovered Conventional Oil and Gas Resources of the World. United States Geological Survey, https://doi.org/10.3133/fs20123042

IEA. CC BY 4.0.

USGS (2012b), Assessment of potential additions to conventional oil and gas resources of the world (outside the United States) from reserve growth. USGS (United States Geological Survey), https://doi.org/10.3133/fs20123052

Ventana Systems Inc. (2026), Vensim, https://vensim.com/

Vossier, A., T. Fasquelle and J. Gordon (2026), Decarbonization versus technological continuity: The implications for global transport, https://www.sciencedirect.com/science/article/pii/S2590174526003685?via%3Dihub

WEPROG (2010), The MSEPS System and its Applications, https://www.weprog.com/information

Wood Mackenzie (2025), Japan Data Centers Power Demand, https://www.woodmac.com/press-releases/japan-data-centers-power-demand/

World Bank (2026a), World Development Indicators (database), https://databank.worldbank.org/source/world-development-indicators

World Bank (2026b), What a Waste 3.0, https://www.worldbank.org/en/publication/what-a-waste

World Bank (2016), Digital Adoption Index, https://www.worldbank.org/en/publication/wdr2016/Digital-Adoption-Index

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