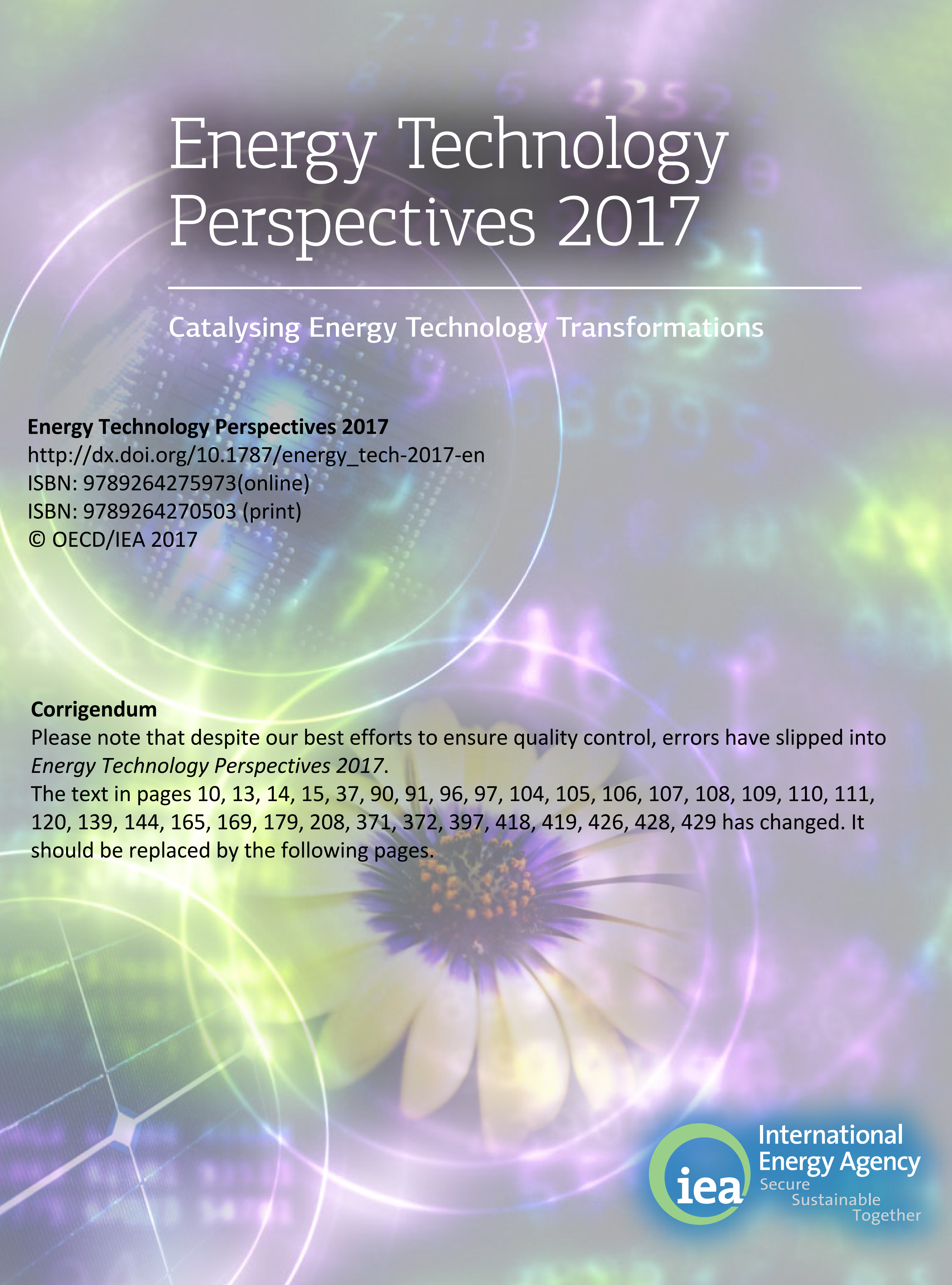

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Catalysing Energy Technology Transformations

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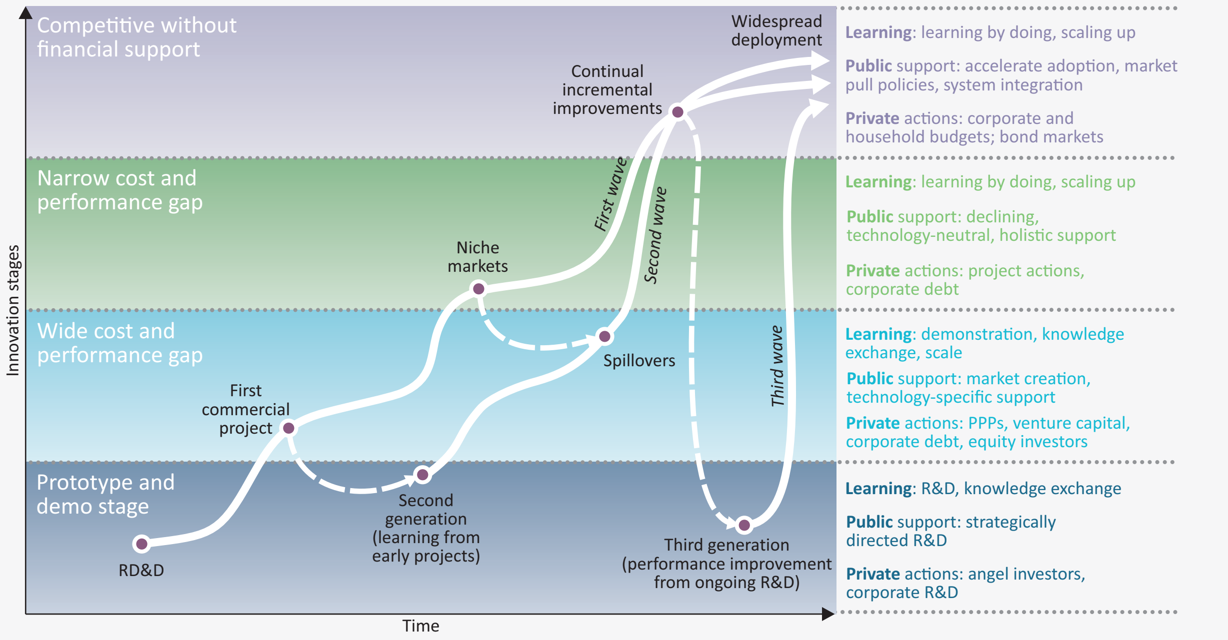
Corrigendum
Please note that despite our best efforts to ensure quality control, errors have slipped into *Energy Technology Perspectives 2017*.
The text in pages 10, 13, 14, 15, 37, 90, 91, 96, 97, 104, 105, 106, 107, 108, 109, 110, 111, 120, 139, 144, 165, 169, 179, 208, 371, 372, 397, 418, 419, 426, 428, 429 has changed. It should be replaced by the following pages.

International
Energy Agency
Secure
Sustainable
Together

Negative emissions, notably in power generation and fuel transformation, become critical as low-carbon ambitions rise. In the B2DS, BECCS delivers almost 5 gigatonnes of "negative emissions" in 2060. These negative emissions are key to the energy sector becoming emissions-neutral by 2060. While BECCS technologies face substantial challenges, they compensate for residual emissions elsewhere in the energy system that are even more technically difficult or costly to abate directly. This will require massive technological learning and scale-up in both sustainable bioenergy and CCS, which have been lagging behind so far.

Innovation must be supported at all stages, from early research to full demonstration and deployment. Both incremental and radical innovations are needed to transition to a new energy system. Governments have an important role in ensuring predictable, long-term support in all stages of innovation – i.e. from basic and applied research through to development, demonstration and deployment phases. Allocation of resources to various technologies must consider both short- and long-term opportunities and challenges for innovation, as well as reflect the level of technology maturity (Figure 1.1).

Figure I.1. Energy technology innovation process



Notes: PPP = public-private partnerships. RD&D = research, development and demonstration. R&D = research and development.

Key point *Energy technologies require support across all innovation stages.*

International co-operation between various levels of governments and with the private sector is essential. Multilateral collaboration can improve the cost-effectiveness of energy technology innovation and build confidence that progress is being achieved at a worldwide scale. Globalisation is sparking more open innovation frameworks that help pool resources to accelerate research and development (R&D), underwrite demonstration, and stimulate faster deployment of proven technologies. Increasing local innovation capacity is essential to the successful deployment of innovative technologies that can help meet local policy and environmental objectives and contribute to global sustainability goals. Existing initiatives, such as the IEA Technology Collaboration Programmes, the Clean Energy Ministerial and Mission Innovation should be properly anchored in all policy decision-making processes.

The Office of Management and Administration, led by Claire Bouteille and including Nathalie Collin, Einar Einarsson, Olivier Parada and Diana Browne, provided support to the project in the areas of finance, human resources and information systems.

The work was guided by the members of the IEA Committee on Energy Research and Technology (CERT), who helped to substantially improve the policy relevance of this document. The technology analysis in this book draws extensively upon the unique IEA Energy Technology Network. Numerous experts from many of the IEA Technology Collaboration Programmes have contributed with data and suggestions.

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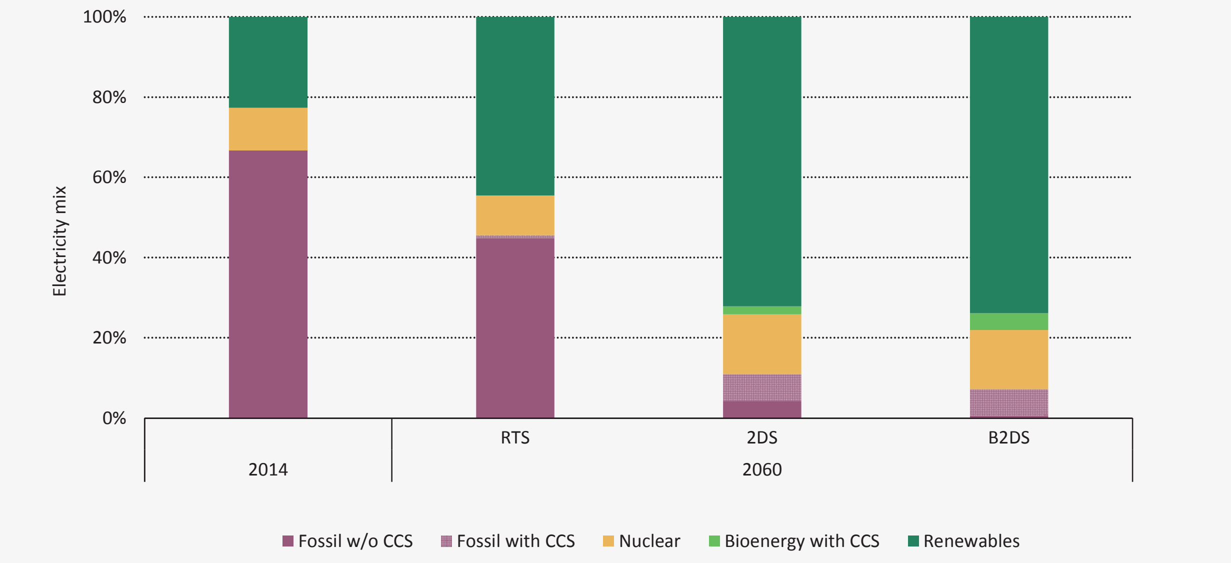
The share of electricity in final energy demand across all end-use sectors almost doubles from 18% today to 35% in the 2DS in 2060, and 41% in the B2DS. The shift is particularly notable in transport, where electricity becomes the primary fuel for on-road vehicles in the B2DS (Figure 1.11). The additional electricity consumption by end-use sectors in the B2DS in 2060 is about 1 700 terawatt hours (TWh) more than the 2DS, equivalent to the combined annual electricity consumption of India and the Russian Federation today.

Decarbonisation of power generation

The shift to electrification in the B2DS increases the pressure on the power sector, not only to accommodate additional generation but to do so while rapidly decarbonising and becoming a source of negative emissions. This transformation will require a considerable change in the traditional trends in power sector investment, with the carbon intensity of electricity generation declining at an average rate of –3.9% in the next decade for the 2DS or –4.5% for the B2DS, compared with –0.5% over the past decade.

In the 2DS, renewables deliver around two-thirds of the emissions reductions achieved in the power sector, with CCS providing 18% and nuclear 16% of reductions. By 2060, 98% of electricity generation is from low-carbon sources (Figure 1.12), with the carbon intensity of generation approaching zero — a colossal effort relative to today's level of around 520 grammes of CO_2 per kilowatt hour (gCO_2/kWh) and the 254 gCO_2/kWh achieved in the RTS. In the B2DS, the carbon intensity of electricity generation falls below zero, to –10 gCO_2/kWh in 2060, effectively making the power sector a source of negative emissions to offset residual emissions in industry and in transport.

Figure 1.12. Power generation fuel mix by scenario, 2014 and 2060



Key point *The fuel mix to generate electricity in the 2DS and B2DS would be vastly different from today's mix.*

Increased development and use of sustainable bioenergy

A significant contribution from sustainably sourced bioenergy is needed as part of the transition to a clean energy future in both the 2DS and the B2DS. Bioenergy can play an important role across the energy sector: in electricity production, in heating for buildings, for industrial uses and in transport.

The role of bioenergy will largely be defined by the availability of sustainably sourced bioenergy feedstock. Its supply will need to grow from 55 EJ today to almost 100 EJ in 2060 in the RTS and to around 145 EJ in both the 2DS and B2DS. While this is within

Fuel economy of LDVs

● Improvement needed

↘ Negative developments

While the average tested fuel economy of new LDVs continues to improve, global progress slowed recently. Since 2014, fuel economy improved faster in non-OECD countries than in the OECD. The gap between on-road and tested fuel economy also widened.[1] To stay on track with the 2DS, fuel use per kilometre (km) for new vehicles must decline by 3.7% per year through 2030.

Recent trends

In 2015, tested fuel consumption[2] of new LDVs in OECD ranged from 5.2 litres of gasoline equivalent (Lge) per 100 km to 9.2 Lge/100 km, with an average across all OECD countries close to 7.6 Lge/100 km. Hence, OECD countries included both the highest and lowest national averages. LDVs sold in North America and Australia use more fuel per kilometre than vehicles sold in other OECD countries.[3] In 2015, the average fuel economies of LDVs sold in most non-OECD countries were clustered close to 7.9 Lge/100 km.

The annual improvement of global average fuel economy of new LDVs slowed during the past decade, from 1.8% in 2005-08 to 1.2% in 2012-15 and to 1.1% in 2014-15 (GFEI, 2017). This slowdown can be mostly attributed to OECD countries, where annual improvement dropped to 1.0% between 2012 and 2015. Conversely, fuel economy improvement in non-OECD countries accelerated to 1.4% per year between 2012 and 2015, and 1.6% annually between 2014 and 2015, due to tightened fuel economy policies in non-OECD markets.[4]

Discrepancies between on-road and tested fuel economy have been a major topic of discussion in recent years. Increasing evidence shows that this gap has been widening since 2001, especially in Europe, more than quadrupling to exceed 40% in 2015 (ICCT, 2016).

Tracking progress

Fuel economy improvement rates were significantly lower, both in OECD and non-OECD countries, than those required to meet the 2030 Global Fuel Economy Initiative (GFEI) target and the ambitions set by the IEA 2DS (GFEI, 2017). Achieving the 2DS vision requires halving the global average tested fuel consumption of new LDVs to 4.4 Lge/100 km by 2030 compared with a 2005 baseline of 8.8 Lge/100 km (the current global benchmark is 7.7 Lge/100km). This level matches an annual reduction in fuel use per kilometre, for new vehicles, of 3.7% between 2015 and 2030. To be in line with 2DS with regard to the global fleet, the global sales-weighted average fuel economy also needs to reach 4.7 Lge/100 km by 2025.

Prospects for further improvements depend on the level of ambition of fuel economy regulations and their market coverage. The 2015 addition of India and Saudi Arabia to the set of countries regulating fuel economies helped to maintain the share of the global LDV market covered by fuel economy standards above two-thirds.

A new test procedure (the Worldwide Harmonised Light Vehicle Test Procedure [WLTP]) has recently been endorsed by the United Nations (UNECE, 2014). Progressive and widespread adoption of this standard will be a first step to reduce the gap between tested and real-world on-road fuel economy.

Recommended actions

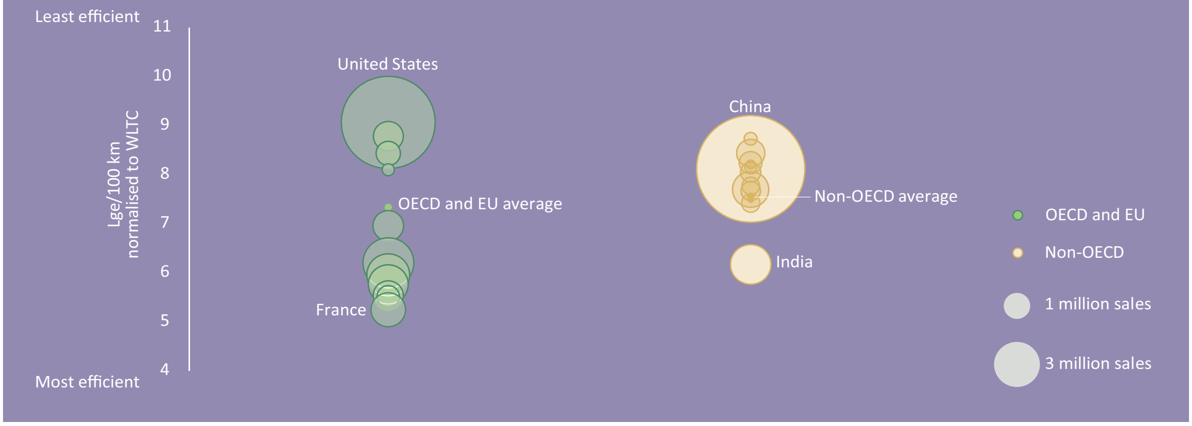
Despite good progress over the past decade in the geographical coverage of countries using fuel economy policies, progress in fuel economy improvement is clearly lagging what is needed for the 2DS. Realigning the development of fuel economies with the GFEI objective is possible with the adoption of policies supporting energy efficiency and the use of fuel-saving technologies.

Key policies include fuel economy standards and vehicle taxes differentiated on the basis of emissions of CO_2 per km. On the technology side, improving fuel economy will require weight reduction, lower rolling resistance tyres and improved aerodynamics. Internal combustion engines can deliver initial savings, but hybrid cars and EVs need to gain market shares to achieve 2DS targets.

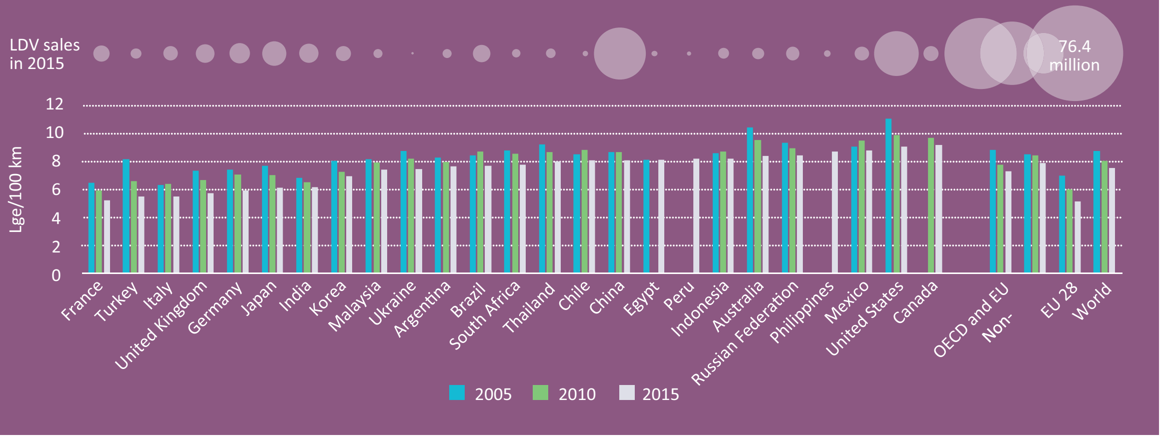
Reducing the gap between tested and on-road fuel economy is essential to meet 2DS targets. This goal requires more ambitious implementation procedures and the monitoring of fuel economy regulations, such as the WLTP, that better reflect real-world vehicle operation. Achieving increased accuracy in real driving conditions will also require the use of on-road testing and confirmatory tests of road load determinations.

1-4. Refer to Technology overview notes on page 108.

2.40 Tested fuel economy numbers for new LDVs and market size, 2015



2.41 Fuel economy development, test values, 2005-15



2.42 Annual fuel economy improvement (Lge/100 km), test values

For sources and notes see page 108

● Not on track
~ Limited developments

Building envelopes

A growing number of countries and local jurisdictions have adopted building energy codes, but two-thirds of countries still do not have mandatory energy codes for the entire buildings sector. Deep energy renovations of existing buildings also continue to fall short of needed progress. Efforts and investments need to scale up dramatically to improve average building envelope performance by 30% by 2025 to keep pace with floor area growth and demand for thermal comfort.

Recent trends

Global building envelope performance[1] (in terms of useful energy per square metre [m^2]) improved by roughly 1.4% per year since 2010. Yet it was outpaced by growth in total building floor area (more than 2.5% per year) and the increasing demand for greater thermal comfort, especially in developing countries. Over the next decade, more than 20% of expected global building additions to 2050 will be built, and more than 50% of those floor area additions will occur in regions that currently do not have mandatory energy codes in place for the entire buildings sector.

Concerted effort is needed to improve global building envelope performance, which has the most influence over heating and cooling needs in buildings. While progress is being made in many countries and municipalities, nearly two-thirds of countries still do not have mandatory energy codes that apply to the entire buildings sector. Enforcement is also a major issue in many countries to achieving high-performance building envelopes, while many existing building energy codes need to be updated or revised to narrow the gap between existing building practices and building envelope targets.

Advancement of deep energy renovations (e.g. 30% to 50% improvement in building envelope performance) of existing buildings also continues to be sluggish, particularly in OECD countries. The buildings sector comprised roughly 230 billion m^2 in 2015, the majority of which will still be standing in 2050. Improvement measures typically pursued today (e.g. window replacements and modest levels of insulation) are a missed opportunity to achieve deep energy savings with cost-effective investments. The rate of annual building energy renovations also needs to improve considerably, from rates of 1% to 2% of existing stock per year today to more than 2% to 3% per year by 2025.

Tracking progress

Global progress in achieving high-efficiency new buildings is slow, particularly in non-OECD countries where the greatest floor area additions are expected to 2050. Much greater effort is needed to support adoption and enforcement of mandatory building energy codes in developing countries, starting first with rapidly emerging economies that risk locking in inefficient building envelope investments over the next decade.

Some notable advancement in 2015 and 2016 includes the ongoing development of building energy codes in several sub-Saharan African countries. Progress in India has also been made to shift from a voluntary national code to locally adopted mandatory codes for non-residential buildings in most Indian states.

Additional progress includes introduction of a low-carbon building label in France in 2016 as well as the introduction of building energy performance certificates in Russia and South Africa. As of 2016, nearly 40 countries had mandatory certification programmes, and as many as 80 countries had voluntary programmes.[2]

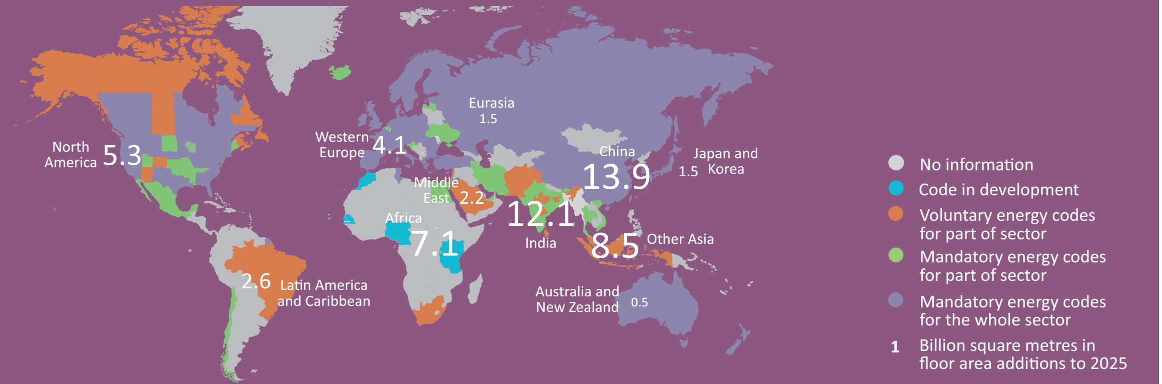
Recommended actions

Clear and consistent signals on building energy performance, along with improved access to finance for high-performance building envelope construction and renovations, are needed to move markets to energy-efficient and low-carbon building envelope investments. Significant effort is needed to quickly adopt and enforce aggressive building energy codes and performance standards in line with 2DS ambitions across all countries. Additional effort is also needed to update many existing building energy codes (both voluntary and mandatory).

Policy makers should also support development and demonstration of advanced and integrated envelope solutions and building practices. Co-operation among governments, especially on harmonisation and improvement of building energy performance standards, can help to provide an assertive signal to markets in line with 2DS building envelope expectations.

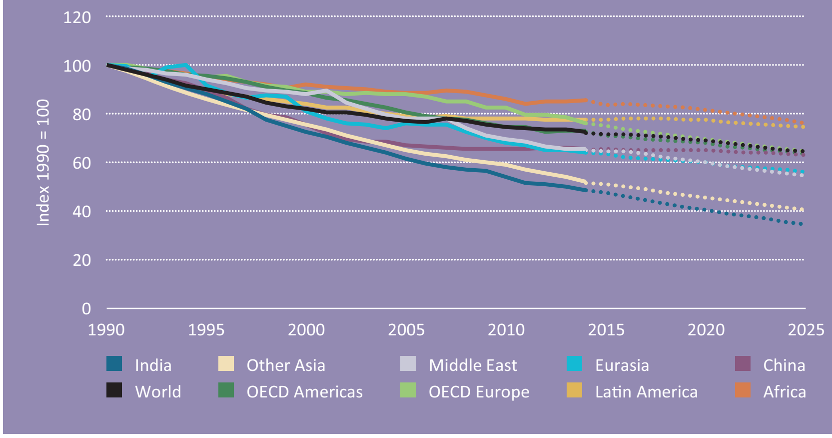
1–2. Refer to Technology overview notes on page 109.

2.49 Building energy codes



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.

2.50 Change in building envelope performance



ONLY

1/3

OF COUNTRIES HAVE MANDATORY ENERGY CODES FOR THE ENTIRE BUILDINGS SECTOR

2/3

OF NEW BUILDINGS NEED TO BE COVERED BY MANDATORY BUILDING ENERGY CODES BY 2025

2.51 Efficiency policy progress, 2005-15

For sources and notes see page 109

Technology overview notes

Unless otherwise noted, data in this report derive from IEA statistics and *ETP* analysis. The *TCEP* dataset for up to 2014 is derived from official IEA statistics, with 2014 the latest year that a full dataset was available. The year 2014 is taken as a base year for estimates and forecasts. Sources for data after 2014 vary by technology type or market. They can be a product of capacity investment analysis or collected sales data, or in some cases are provisional estimates based on forecasts and market trends.

The notes in this section provide additional sources and details related to data and methodologies. Throughout the report, annual averages are calculated as compound average growth rates.

Renewable power (page 64)

Figures 1,2,3 and 4 sources: data from IEA (2016c), Medium-term Renewable Energy Market Report and 2°C Scenario (2DS) targets from 2017 ETP model.

Nuclear power (page 68)

Note 1: This effect is evident elsewhere, but it seems to be most acute in the United States. However, two states facing eminent closures – Illinois and New York – took action to allow nuclear to receive low-carbon financial incentives to maintain existing capacity.

Note 2: A documentation and quality control issue reported to the French regulator by Areva concerning its Creusot foundry prompted safety reviews at reactors using the facility's components in France and in several other countries. So far, French and other national regulators have not found any issues that pose a safety risk in their opinion, but the issue caused significant disruptions to the operation of the French fleet, in particular.

Note 3: To bridge this gap using wind and solar, for instance, would require 200 gigawatts electrical (GW_e) to 250 GW_e of additional capacity.

Coal-fired power (page 72)

Note 1: Coal generation in China is estimated to have rebounded again in 2016.

CCS (page 74)

Note 1: CO_2 is captured, compressed and transported for injection into onshore oilfields for injection for EOR. EOR is a closed-cycle process that involves injecting carbon dioxide (CO_2) into older oil reservoirs to increase or prolong production. The CO_2 is injected into the reservoir, recovered from the produced oil and re-injected. CO_2 is retained and eventually stored through injection for EOR, though additional monitoring and planning is needed to verify the CO_2 is stored effectively and accounted for.

Note 2: The captured CO_2 is transported by pipeline 82 miles and injected into depleted fields for EOR purposes. See Note 1.

Note 3: This three-year CO_2 injection programme is scheduled for 2016-18, with monitoring continuing for another two years until 2020.

Note 4: These two projects, the Kemper Project in the United States and the Gorgon CO_2 Injection Project in Australia, will be capable of capturing up to 6.5 $MtCO_2$ per year.

Note 5: In 2016 the government completed a feasibility study on three industrial emission sources and the associated transport and storage options. They also announced a three-year extension to the Technology Center Mongstad (TCM) test facility, a joint venture between the Norwegian state, Statoil, Shell and Sasol.

Note 6: Only 9.3 million tonnes of the captured CO_2 is being stored with appropriate monitoring and verification focussed on verifying the long term retention of CO_2. Such monitoring and verification is not always the case for EOR projects. See Note 1.

Figure 2.14 and 15: Source: GCCSI (2015), *The Global Status of CCS 2015*. Note: large-scale projects are defined in accordance with the Global Carbon Capture and Storage

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

Figure 2.16: Note: Data are in USD 2015 prices and purchasing price parity (PPP).

Figure 2.17: Source: IEA analysis based on BNEF (2015), Funds Committed (private database). Note that total project investment is in nominal USD and is recorded at the point of final investment decision.

Industry (page 76)

Note 1: Including process and feedstock-related emissions.

Note 2: Unless otherwise noted, all numbers are derived from the IEA, 2017a.

Note 3: Industry 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), construction and manufacturing. Petrochemical feedstock energy use and blast furnace and coke oven energy use are also included.

Note 4: World Steel (2016).

Note 5: Calculated based on the Cement Sustainability Initiative (CSI) Getting the Numbers Right database, in combination with estimates from national associations for regions with less coverage. Source: Cement Sustainability Initiative (CSI), 2017.

Note 6: IAI (2017), World Aluminium Statistics, The International Aluminium Institute, London, www.world-aluminium.org/statistics/.

Note 7: IAI (2016), Global Mass Flow Model, The International Aluminium Institute, London, www.world-aluminium.org/publications/.
This represents the share of production based on new and old scrap. Internal scrap has been excluded for consistency with published statistics.

Figure 2.18: Petrochemical feedstock energy use and blast furnace and coke oven energy use are included.

Figure 2.19: Petrochemical feedstock energy use and blast furnace and coke oven energy use are included, as well as process and feedstock-related emissions.

Figure 2.20: Petrochemical feedstock energy use and blast furnace and coke oven energy use are included. "Heat" refers to commercial heat purchased from heat networks. Heat generated on site is included in fuel terms. "Electricity" includes all electricity consumption, including the electricity generated on site. Generation from black liquor in recovery boilers is included in "heat" and "electricity".

Figure 2.21: Process CO_2 emissions from lime kilns in the pulp and paper sector are considered carbon-neutral because they are from biogenic sources of lime from the sector's raw materials, and thus they are not included in this figure. Other sources of process CO_2 emissions exist in the industrial sector; this includes only process CO_2 from the five energy-intensive sectors.

Textbox 1: Chemicals and petrochemicals, iron and steel, non-ferrous metals, non-metallic minerals, and pulp, paper and printing. Included here are energy use in blast furnaces and coke ovens and as petrochemical feedstock.

Textbox 2: Based on IEA estimates from energy-intensive industrial sector modelling.

Chemicals and petrochemicals (page 80)

Note 1: "Primary chemicals" includes: ethylene, propylene, benzene, toluene and xylenes, ammonia and methanol. These chemicals form the basis of the modelling for the sector.

Note 2: HVCs include: light olefins (ethylene and propylene) and BTX aromatics (benzene, toluene and xylenes).

Note 3: The weight of feedstocks is determined by the length of their constituent hydrocarbon chains. Lighter feedstocks include natural gas, ethane and LPG. Heavier feedstocks include naphtha and fuel oil.

Note 4: SEC: process energy consumption per tonne of primary chemical(s) in GJ/t.

Note 5: IEA estimates based on regional modelling results. SEC values for HVCs include the methanol-to-olefins route. The large ranges of SEC for a given chemical can be primarily attributed to the range of feedstocks used in different regions. Processes fed by heavier feedstocks generally incur a process energy penalty per unit of chemical produced, compared with a process producing the same chemical with a lighter feedstock.

Note 6: Final energy consumption includes both process energy and fuel use as feedstock. Emissions are calculated based on fuel combustion and stoichiometric calculations to compare carbon content of feedstocks and products. Emissions from oxidised chemicals-based products, such as plastics used in waste-to-energy facilities, are accounted for in other sectors.

Figure 2.25: “Other” feedstock shares for HVCs include gas oil for steam cracking, ethanol dehydration, and methanol to olefins. “Naphtha” includes both feedstock for steam cracking and catalytic cracking. For methanol, coke oven gas constitutes the “Other” category.

Figure 2.26: Production volumes for HVCs only include those produced in the chemical and petrochemical sector. Both the propylene and BTX aromatics components of HVCs have significant shares sourced from the refining sector. The energy intensities shown do not cover these quantities.

Pulp and paper (page 82)

Note 1: IEA analysis focuses on pulp and paper manufacturing, which makes up the majority of pulp, paper and printing sector energy use.

Note 2: This share of wood pulp in total fibre furnish does not include fillers.

Note 3: Pulp and paper amounts are referred to in air-dried tonnes, with 10% moisture content. Kraft pulping (or sulphate pulping) is the conversion of wood into pulp, breaking the bonds between lignin, hemicellulose and cellulose with a solution of sodium hydroxide and sodium sulphide.

Note 4: Black liquor is a by-product from kraft pulping. It is an aqueous solution of sulphate chemicals used in the pulping process and lignin and hemicellulose residues extracted from wood.

Figure 2.29: FAO (2016). SEC ranges are indicative of the scale of national average energy intensity. They are based on IEA analysis, not reported data. SEC includes energy for paper machines and for pulpers. Chemical recovery, pulp drying, wood processing, and other energy use are not included.

Transport (page 84)

Note 1: In high-income countries, which account for 20% of the mitigation measures proposed in NDCs, nearly 50% of mitigation strategies target fuel efficiency improvements or decarbonising fuels. Low- and middle-income countries often opt for import restrictions based on vehicle age and fuel efficiency measures.

Note 2: Progress on HDVs has been encouraging, with indications of efforts to draft legislation to address the energy efficiency of trucks in Europe, India and Korea. However, only Canada, China, Japan and the United States have actually put in place HDV fuel economy standards to date.

Note 3: Offset mechanisms include both carbon credits and carbon allowances from emissions trading systems.

Note 4: Implications of this decision for the maritime fuel mix and prospects for low-carbon alternative fuels are discussed in the “International shipping” section.

Note 5: Continued CO_2 emissions growth in non-OECD countries is commensurate with increasing transport activity, driven mainly by rising incomes and population growth.

Note 6: The CO_2 emissions cited here are evaluated on a tank-to-wheel basis, under a framework that includes combustion emissions of biofuels (and wherein well-to-tank GHG intensity of biofuels may offset combustion emissions).

Note 7: Vehicle efficiency (or fuel economy) regulations should first and foremost target the most energy-intensive modes of passenger and freight transportation (namely, passenger cars and heavy-duty trucks).

Note 8: A sizeable potential to reduce specific CO_2 emissions in international shipping comes from considerable scope within the sector for efficiency improvements, as well as the availability of renewable solutions such as wind assistance.

Electric vehicles (page 86)

Note 1: The term "EV market share" refers in this section to the share of electric car sales in total PLDV sales.

Note 2: In this section, electric cars refer to plug-in electric passenger light-duty vehicles (PLDVs), and comprise full BEVs and PHEVs. "Electric cars" are also commonly referred to as EVs.

International shipping (page 88)

Note 1: Expressed in constant PPP-adjusted USD.

Note 2: International shipping energy demand reached 8.2 EJ in 2014, up from 6.5 EJ in 2000.

Note 3: The global fleet size grew between 2010 and 2015; the most significant growth took place for container ships. The average container ship size grew at an annual rate of 18.2% between 2010 and 2015, compared with 1.9% between 2001 and 2009 (UNCTAD, 2016), allowing for fewer ships to satisfy global freight demand.

Note 4: It mandates a minimum improvement in the energy efficiency per tonne kilometre of new ship designs of 10% by 2015, 20% by 2020, and 30% by 2025, benchmarked against the average efficiency of ships built between 1999 and 2009.

Note 5: In 2014, HFO accounted for 84% of the marine bunkers fuel mix. HFO has an average sulphur content of 2.5%.

Note 6: This effect is measured in megajoules per vehicle kilometre, rather than tonne kilometre, to exclude the effect of increasing average ship size. The 1% fuel efficiency increase excludes the effect of projected growth of average ship size and freight capacity. The assumption underlying this calculation is that each ship abides by the efficiency standard as prescribed: 10% more fuel efficient between 2015 and 2020, 20% more efficient between 2020 and 2025, and 30% more efficient between 2025 and 2030.

Note 7: Most of the reduction took place after 2010 and can most likely be attributed to an unexpected issue of overcapacity in the wake of the financial crisis, which pushed numerous older and less efficient ships into an early retirement.

Note 8: Possible exceptions, where low-SO_x technologies may also contribute to GHG mitigation, include advanced biofuels, low-carbon synthetic fuels and, to a much lesser extent, LNG.

Note 9: Other low-carbon energy carriers, such as low-carbon synthetic fuels or hydrogen, could also complement these solutions.

Note 10: To stay on track with the 2DS, the emissions from the sector must remain below 800 $MtCO_2$ in 2025.

Note 11: IMO is the United Nations (UN) agency responsible for regulating international shipping.

Note 12: For example, switching to LNG and scrubbers could help to reduce local air pollution, but these measures would be inadequate to bring the sector's carbon emissions trajectory in line with the 2DS. On the other hand, energy efficiency, wind assistance, advanced biofuels, low-carbon synthetic fuels and hydrogen could help to meet both the needs of pollutant emissions mitigation requirements and to achieve significant GHG emissions reduction.

Fuel economy of LDVs (page 90)

Note 1: The values used here are expressed on the basis of a normalisation of regional test procedures to the Worldwide Harmonized Test Cycle, based on the conversion factors developed by ICCT (2014).

Note 2: The widening gap between on-road and tested fuel economy is especially relevant for vehicles being tested according to the European test cycle, also used in the UN framework and now migrating towards the Worldwide Harmonized Test Cycle, partly with the aim to address this gap.

Note 3: This is largely attributable to the greater weight, footprint and power rating of LDVs sold in these markets, and matches the lower price of fuel in comparison with other OECD countries.

Note 4: This correlates with tightened fuel economy policies in non-OECD markets enacted over the past few years (such as China and Brazil), and with China's increasing share of the LDV market (GFEI, 2017). The slowdown in global fuel economy improvement rates also matches falling oil prices in the second half of 2014 and 2015.

Transport biofuels (page 92)

Note 1: Sustainably produced biofuels offer a lower-carbon-intensity alternative to petroleum-derived fuels. Conventional biofuels include sugar- and starch-based ethanol and oil crop-based biodiesel. Advanced biofuels are sustainable fuels produced from non-food crop feedstocks, which are capable of delivering significant life-cycle GHG emissions savings compared with fossil fuel alternatives, and which do not directly compete with food and feed crops for agricultural land or cause adverse sustainability impacts.

There is currently no globally recognised definition for advanced biofuels, with different interpretations of the term, as well as alternative terminology such as second-generation biofuels in use. Classification as "advanced" does not necessarily infer greater sustainability versus all conventional biofuels per se, as biofuel sustainability must be judged on the individual characteristics specific to each production pathway. However, where waste and residue feedstocks are used, GHG emissions associated with land-use change are avoided.

The United States and Brazil combined accounted for over 70% of global conventional biofuel production in 2016. In the US Renewable Fuel Standard, total renewable fuel volumes for 2017 indicate that the limit for corn-based ethanol of 15 billion gallons will be reached. Structural challenges relate to availability of suitable vehicles and fuel distribution infrastructure. Flexible-fuel vehicles have suitable engine modifications to use higher ethanol blends (e.g. E85), or as is commonly found in Brazil, pure hydrous ethanol (E100). Brazil's NDC for the Paris Agreement outlines that the share of sustainable biofuels in its energy mix will be increased to approximately 18% by 2030. Examples of markets where biofuels mandates and supportive policies have been strengthened since the downturn in global crude oil prices include Argentina, Brazil, India, Indonesia, Spain and Thailand.

While emissions from aviation do not sit within the Paris Agreement, the International Air Transport Association (IATA) has adopted its own set of ambitious targets to reduce the climate impact from air transport, including carbon-neutral growth from 2020 and a reduction in net aviation CO_2 emissions of 50% (on 2005 levels) by 2050.

Examples of ambitious and long-term transport sector targets include Finland's aim for a 30% biofuels contribution in transport and Sweden's ambition of a vehicle stock independent of fossil fuels, both by 2030. Examples of policies to establish defined reductions in the life-cycle carbon intensity of transportation fuels include the Low Carbon Fuel Standard in California and Climate Protection Quota in Germany. Several EU member states have recently established advanced biofuels mandates, including Denmark (from 2020) and France (from 2018). These complement policies already established in Italy (from 2018) and the United States.

The Biofuture Platform aims to facilitate international policy dialogue and collaboration to facilitate the deployment of sustainable low-carbon alternatives to fossil fuels in transport. The Below50 collaboration initiative from the World Business Council for Sustainable Development, in partnership with Sustainable Energy for All and the Roundtable on Sustainable Biofuels, has been established to work with the biofuels industry to promote sustainable fuels that are a minimum of 50% less carbon-intensive than conventional fossil fuels. Examples of sustainability indicators include those developed by the Global Bioenergy Partnership, while an example of a strong governance framework is the EU sustainability criteria for biofuels.

Note 2: Y-o-y growth 2015-16 from IEA (2017b).

Buildings (page 94)

Note 1: More information can be found in the *Global Status Report 2016* of the Global Alliance for Buildings and Construction at www.globalabc.org.

Figure 2.46: Source: derived with IEA (2016), *IEA World Energy Statistics and Balances* (database), www.iea.org/statistics. Notes: CO_2 = carbon dioxide; TJ = terajoule (1 012 joules); EJ = exajoule (1 018 joules); building carbon intensities represent emissions from direct energy consumption as well as indirect emissions from final energy consumption of electricity and commercial heat; other renewables include modern biofuels and solar thermal energy; this map is without prejudice to the sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

Figure 2.47: Sources: population: UN DESA (2015), *World Population Prospects: The 2015 Revision, Medium-Fertility Variant*; energy decomposition calculations derived with IEA (2016), *IEA World Energy Statistics and Balances* (database), www.iea.org/statistics. Notes: EJ = exajoule (1 018 joules); the energy decomposition represents the influence of each factor (e.g. population) on changes in total final energy demand since 1990; household occupancy reflects the decreasing average number of persons per household; other represents energy demand factors, including improved access to commercial fuels (in developing countries), changes in climate (i.e. annual average heating and cooling degree days) and changes in energy service provision (e.g. greater demand in total luminous flux per square metre); energy efficiency includes both increases in product performance (i.e. technical efficiency) as well as shifts from less efficient equipment to more efficiency technology (e.g. gas boiler to heat pump); final energy change is the annual change in final energy consumption relative to 1990.

Figure 2.48: Source: historical energy derived with IEA (2016), *IEA World Energy Statistics and Balances* (database), www.iea.org/statistics.Notes: MWh = megawatt-hour; other renewables include modern biofuels and solar thermal energy; building energy per person represents total final energy per capita (not climate-corrected).

Building envelopes (page 96)

Note 1: Average building envelope performance represents the physical performance of the building envelope (the parts of a building that form the primary thermal barrier between the conditioned interior and exterior) with respect to how much energy is needed to heat and cool a building.

Note 2: More information can be found in the *Global Status Report 2016* of the Global Alliance for Buildings and Construction at www.globalabc.org.

Figure 2.49: Notes: Floor area additions represent the expected number of square metres to be added to the 2015 building stock by key region to 2025; further work on building energy code country inclusion and distinction by level of code is ongoing, and feedback is welcome; this map is without prejudice to the sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area. Source: IEA building code analysis and IEA (2015), *IEA Building Energy Efficiency Policies (BEEP) Database*, www.iea.org/beep/.

Figure 2.50: Notes: Average building envelope performance represents the physical performance of the building envelope (the parts of a building that form the primary thermal barrier between the conditioned interior and exterior) with respect to how much energy is needed to heat and cool a building; the evolution of average building envelope performance is compared to 1990, where annual global average building envelope performance (in useful energy per square metre [m^2], climate corrected) was roughly 155 kilowatt-hours per m^2 in 1990. Source: historical energy derived with IEA (2016), *IEA World Energy Statistics and Balances* (database), www.iea.org/statistics.

Figure 2.51: Notes: progress is shown as the percent improvement in building envelope thermal resistance requirements from 2005 to 2015 weighted (using building energy use, envelope area and thermal resistance) by building end-use and envelope components; the proximity to target shows the percent achieved toward requiring a nearly zero-energy building envelope; policy progress shown here for the United States, Canada and China only considers the cold climate zones of those countries. Source: IEA building code analysis and IEA (2015), *IEA Building Energy Efficiency Policies (BEEP) Database*, www.iea.org/beep/.

Lighting, appliances and equipment (page 98)

Note 1: Building equipment includes energy-consuming technologies for heating, cooling and ventilation; cooking; hot water; and other electrical plug loads and equipment (e.g. office equipment, medical devices, information technology networks and electric motors) used in buildings. It does not include traditional use of biomass.

Note 2: Household size represents the decreasing average number of persons per household (and, therefore, more households).

Figure 2.52: Notes: Co-efficient of performance (COP) represents the energy efficiency ratio (watts in cooling equivalent per watt of electricity consumption): the higher the COP, the greater the energy-efficiency. Annual average growth in space cooling demand represents the expected change in useful cooling energy demand between 2015 and 2025 under the 2DS.

Figure 2.53: Notes: LED = light-emitting diode; LFL = linear fluorescent lamp; CFL = compact fluorescent lamp. Source: IEA estimates based on on-going data discussions with lighting partners, including the United Nations Environment En.lighten programme and Philips and Osram lighting.

Figure 2.54: Notes: EJ = exajoule (1 018 joules); the energy decomposition represents the influence of each factor (e.g. population) on changes in total final energy demand since 1990; household occupancy reflects the decreasing average number of persons per household; other represents other energy demand factors, including improved access to electricity (in developing countries), increases in appliance ownership and changes in technology choice (e.g. larger refrigerators and televisions); energy efficiency represents increases in product performance (i.e. technical efficiency) which can include shifts to more efficiency technology (e.g. televisions using light-emitting diodes); final energy change is the annual change in final energy consumption relative to 1990.

Renewable heat (page 100)

Note 1: The figures for renewable heat are based on renewables reported in IEA statistics under TFEC. Direct use excludes renewables used in commercial heat (i.e. heat sold and delivered to end users, for example through district heating) and renewable electricity used for heating. In 2014, renewables in district heating accounted for around 1 EJ. The figure for the European Union does not match the share reported under the progress reporting for the Renewable Energy Directive, which applies a different methodology (e.g. it includes heat pumps).

Note 2: This tracking excludes the traditional use of biomass, which continues to play a major role in sub-Saharan Africa and parts of Asia, especially in rural areas where it is used mainly for cooking. The analysis focuses on “modern” biomass used for space and water heating in residential and commercial buildings, as well as all biomass used for process heat applications in industry and agriculture. Biomass use for heat can vary significantly from year to year depending on winter weather. For example, across much of Western Europe, average winter temperatures in 2014 were higher than in 2013, thus resulting in a 11% decrease in residential biomass use.

Note 3: Data for total installed global solar thermal collector capacity are estimated based on data from several sources including *Solar Heat Worldwide* published by the IEA Solar Heating and Cooling Programme, www.iea-shc.org/solar-heat-worldwide.

Figure 2.55: Note: this map is without prejudice to the sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

Figure 2.56: “Other renewable heat” includes geothermal heat across all sectors, solar heat in industry and all renewable heat sources in agriculture.

Figure 2.57: Source: AEBIOM (2016), *AEBIOM Statistical Report 2016*, AEBIOM, Brussels.

Energy storage (page 102)

Note 1: From the integrated energy companies, Total agreed to acquire French battery manufacturer and storage-project developer Saft Groupe for 950 million euros (USD 1.1 billion), while Engie acquired an 80% stake in Green Charge Networks. Large equipment providers also invested, including an estimated USD 50 million investment by GE Ventures in German behind-the-meter storage provider Sonnen. The trend also solidified on the manufacturing side, as large diversified energy storage companies including LG Chem, Samsung SDI and NGK Insulators accounted for 70% of total installed capacity.

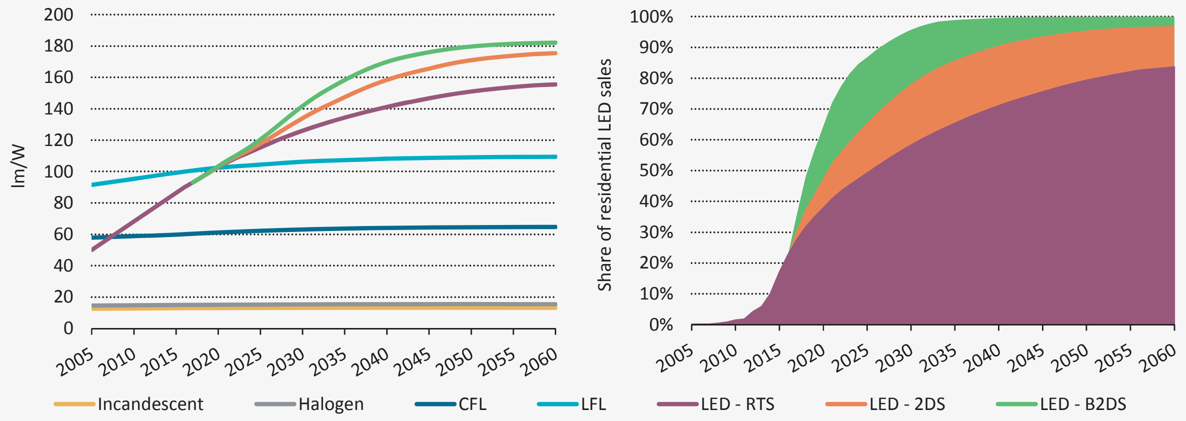
- **Enabling rapid efficiency measures in the Beyond 2°C Scenario (B2DS) would reduce global buildings energy demand by an additional 12% below the 2DS in 2060, or one-third beyond the RTS.** Major shifts away from coal, oil and natural gas amount to more than 23 billion tonnes of oil equivalent (Gtoe) (965 EJ) in cumulative fossil fuel reductions to 2060 compared with the RTS.
- **Rapid deployment of high-efficiency lighting, cooling and appliances in the B2DS would save 50 EJ in electricity demand between now and 2030 – or nearly three-quarters of global electricity demand today.** Those savings would allow greater shifts to electricity without additional burden to the power sector.
- **Buildings-related emissions reduction in the B2DS represents more than 275 $GtCO_2$ in cumulative savings compared to the RTS – more than all the CO_2 emissions produced by the global energy sector from 2006 to 2014.** Shifts away from fossil fuels account for 21% of the reductions, while aggressive uptake of efficiency measures supports power sector decarbonisation in the face of rapidly growing electricity demand.
- **Natural gas demand in buildings in the B2DS could be reduced by as much as 80% by 2060 compared to today.** A strategic vision would be necessary to: avoid growth in gas demand; shift demand to efficient, renewable and integrated solutions (e.g. heat pumps and district energy); and decarbonise remaining gas supply (e.g. by switching to biogas).

Opportunities for policy action

- **National and local authorities across all countries should urgently establish and enforce mandatory building energy codes that apply progressively tighter energy performance standards for both new and existing buildings.** A sound balance among regulatory instruments, incentives (e.g. tax credits) and financing tools, capacity-building initiatives, and technological innovation is needed to accelerate widespread adoption of low-carbon, high-efficiency buildings practices and technology solutions.
- **Significant action is needed to expand existing policies and regulations for energy-consuming equipment and buildings technology (e.g. window performance).** Labelling and minimum energy performance standards (MEPS) should be expanded to cover the vast majority of buildings end uses, while existing MEPS should be strengthened.
- **Governments can advance uptake of energy-efficient, low-carbon buildings technologies through appropriate policy packages and market incentives.** Those programmes, including research, development and deployment strategies to improve buildings performance at affordable prices, should seek to bring to market widespread adoption of high-performance buildings technologies and services.
- **The ambitious B2DS would require swift, unprecedented policy action, including suitable pricing signals, to drive innovation and move markets quickly to low-carbon, high-efficiency technologies and best buildings practices.** Clear, consistent and long-term signals to consumers and manufacturers are needed to maximise energy efficiency investments and avoid locking in inefficient, carbon-intensive assets.
- **Transitions away from fossil fuel use in buildings would require long-term strategic thinking and co-ordination.** Governments would need to set forth clear expectations on buildings energy performance and carbon intensity, especially given the long life of buildings and energy distribution assets (e.g. gas networks).

Under the B2DS, energy efficiency measures, including building envelope improvements, represent nearly 2 400 EJ in cumulative energy offsets to 2060 relative to 2014 – more than all the final energy consumed by the buildings sector over the last 20 years. Nearly 70% of those reductions come from the adoption of high-performance equipment in buildings, where slightly less than one-third (or 610 EJ in cumulative savings to 2060) are due to enhanced technology performance (e.g. improvements in very high-efficiency heat pump technologies). Market scale, continued R&D and greater value for energy efficiency (e.g. return on investment) all incentivise further development of even higher performance in buildings technology solutions. When growing population, floor area and buildings activity are all taken into account, the total impact of energy efficiency measures across the global buildings sector in the B2DS contributes to a net cumulative energy reduction potential of 270 EJ in effective energy savings to 2060, equivalent to the last two years of TFEC across IEA member countries.

Figure 3.11. Lighting equipment performance and residential LED market share to 2060



Note: LFL = linear fluorescent lamp.

Key point *Rapid deployment of energy-efficient LED technologies in the B2DS creates critical mass in the market, helping to drive R&D for improved energy performance.*

Rapid adoption of the most efficient buildings end-use technologies, including best available lighting, cooling and household appliances today, underpins the energy savings and emissions reduction potential in the B2DS. Unlike the 2DS, in which those technologies are progressively deployed over the next 10 to 20 years, the B2DS requires a speedy uptake of energy efficiency measures, starting first with off-the-shelf products that can already be adopted in most markets today, such as LED lighting products and solutions (Figure 3.11). This would require significant policy action, including wide-ranging MEPS to address continued availability of less efficient products, and market incentives to help address the traditional consumer decision-making process, which often considers upfront costs over life-cycle cost-effectiveness. Those wide-ranging measures may be unprecedented in many countries, yet the energy offsets available from rapid deployment of high-efficiency lighting, cooling and appliances alone are more than 80 EJ (cumulative) over the next 15 years, and the life-cycle costs for those high-performance technologies are already economically viable in many markets (aside from the other benefits of energy efficiency measures).

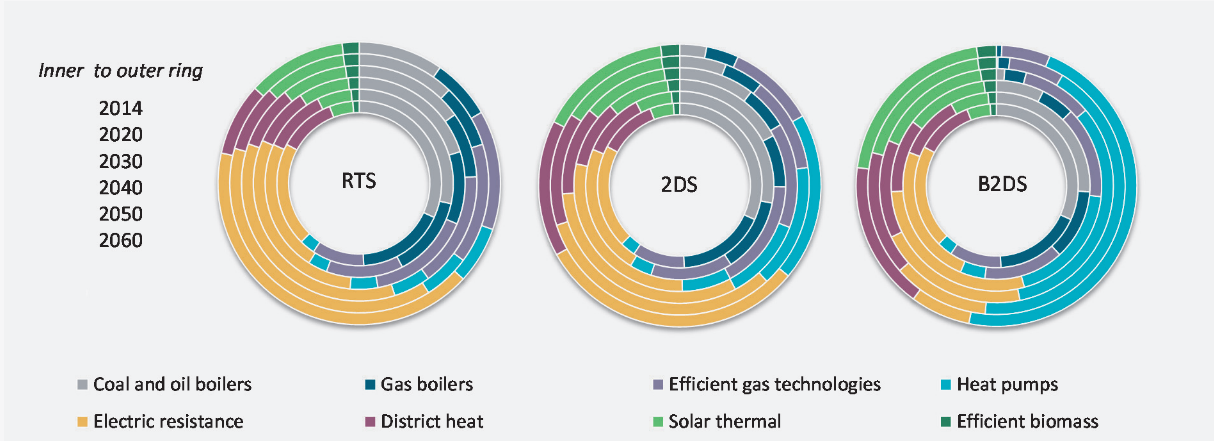
A “race to the moon” for high-performance technologies over the next decade would also help to bring forward more efficient products and technology solutions (e.g. advanced lighting controls), in the same way that past R&D programmes and market incentives helped to bring to market current BATs. For example, LED lighting efficacy (measured in lumens per watt [lm/W]) is expected to increase to around 150 lm/W in the RTS (in line from traditional use of solid biomass to low-cost and readily accessible fossil fuels (e.g. LPG). Global initiatives, such as the Clean Energy Ministerial Global Lighting and Energy Access Partnership (LEAP)[30] and the Efficiency for Access coalition,[31] can help developing countries leapfrog existing technologies to bring affordable and sustainable energy access (e.g. shifting traditional use of solid biomass to solar cookers or solar thermal systems) and ensure a clean and efficient energy transition.

Avoid, shift and improve: Strategies for reducing fossil fuel use in buildings

Just over one-third (35% or 45 EJ) of final energy consumption in the global buildings sector in 2014 was from direct fossil fuel use, and three-quarters of that was for heating purposes (excluding cooking). When traditional use of solid biomass is excluded, more than two-thirds of final energy demand for space and water heating in buildings was provided by fossil fuels, and if average operating efficiencies (e.g. 80% to 90% for gas boilers) are taken into account, this means that roughly 60% of heating equipment in the global building stock today is fed by coal, oil or natural gas (Figure 3.12).

Coal and oil boilers, while still common in certain regions, such as China, Eastern Europe and certain parts of the United States, have increasingly been phased out over the last two decades, as many buildings have shifted to gas boilers (providing around one-third of final energy demand for heating in 2014) and electricity (providing around 10% of final energy demand for heating in 2014). Less common have been shifts to renewable technologies, such as efficient biomass[32] (e.g. pellet stoves) and solar thermal heating, although some regions have made exceptional progress in recent years. For instance, use of solar thermal equipment in buildings has doubled in China since 2010.[33]

Figure 3.12. Evolution of heating equipment in buildings to 2060



Notes: Heating in buildings represents space and water heating; it excludes cooking and other end uses. Efficient gas technologies include gas condensing boilers, gas instantaneous equipment and gas heat pumps. Traditional use of solid biomass is not included.

Key point *The B2DS represents a strategic shift away from fossil fuel equipment to high-efficiency and renewable technologies, such as heat pumps, solar thermal and modern district energy.*

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[30] Further information can be found at www.cleanenergyministerial.org/Our-Work/Initiatives/Energy-Access.

[31] Further information can be found at www.efficiency4access.org/about/.

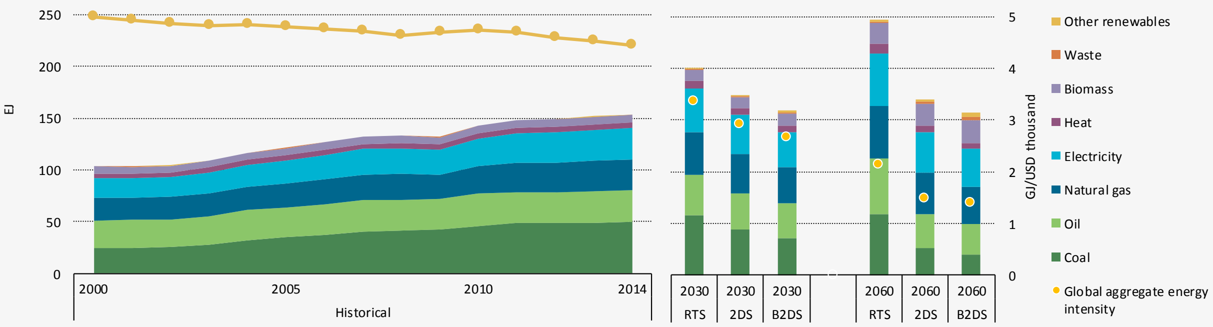
[32] Efficient biomass heaters, such as high-performance fireplaces, masonry stoves and pellet stoves, can achieve burn efficiencies of as much as 90% or more, while maintaining high temperatures over long periods of time (IEA, 2013b).

[33] Despite significant growth over the last decade, the rate of new installations of solar thermal technology in buildings has slowed down in the last two years due to less rapid growth in China. See Chapter 2, "Tracking clean energy progress".

Decarbonisation pathways

The levels of climate change ambition expressed in the Paris Agreement require a much more ambitious pathway for the energy system than the current and announced policies and targets in the RTS imply. The energy demand and CO_2 emissions reduction needed to reach the 2DS pathway or a more ambitious climate target are significantly deeper. The annual improvements in aggregated energy intensity in the industry sector since 2000 would need to triple to meet a 2DS trajectory and almost quadruple to meet the more ambitious B2DS pathway through 2030 (Figure 4.2). The contribution of fossil fuels to the overall energy mix in industry, which has remained nearly flat since 2000, would need to fall by 4–7% over the next 15 years to avoid the more costly 2DS or B2DS trajectories in the long term, which would require much more drastic technological and structural changes to reduce CO_2 emissions in the post-2030 period. Without early action, as more carbon-intensive capacity in industry is installed, stranded assets or costly retrofits are likely in order to shift to a less carbon-intensive industry sector and compensate for early CO_2 emissions by reducing more dramatically in later time periods.

Figure 4.2. Energy use and aggregated energy intensity in industry per value added by scenario



Notes: Final industrial energy use includes blast furnaces (BFs), coke ovens (COs) and petrochemical feedstocks. Energy intensity is given in gigajoules (GJ) per thousand United States dollars (USD) of aggregated industrial value added.

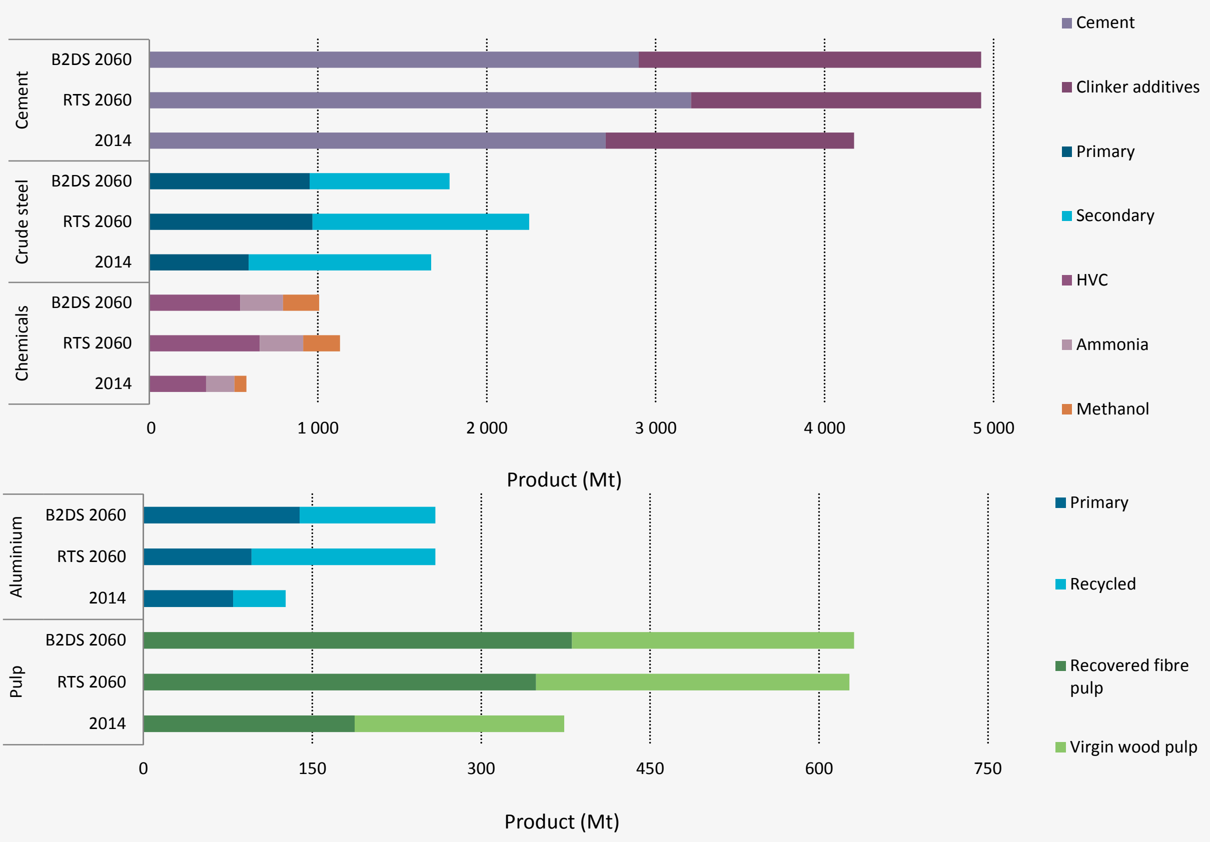
Source: IEA (2016), *World Energy Balances 2016*.

Key point *Final industry energy intensity decreases dramatically by 2060 in the low-carbon scenarios.*

In the 2DS, global direct CO_2 emissions from industry are reduced by 44% by 2050 and halved by 2060 compared with the RTS. However, to reach net-zero CO_2 emissions at the system level, by 2060, which is required for the B2DS, industry would need to further reduce its carbon emissions by 69% by 2050 and 80% by 2060 compared with the RTS (Figure 4.3). These reductions would have to include efforts to address process CO_2 emissions, generated in industrial processes from the use of carbon–based raw materials, which accounted for 23% of total CO_2 emissions in industry in 2014, in addition to emissions from fuel combustion. Such an ambitious change in the direct CO_2 intensity of industrial activity will need to occur along with development of new infrastructure and sustainable consumer products, which will require considerable amounts of material commodities to be produced and adapted to new applications.

rates include the cost and time to develop infrastructure, stimulating behavioural change and technical issues related to the quality of scrap.

Figure 4.5. Global material production projections in the RTS and B2DS



Notes: HVC = high-value chemicals. HVC refer to ethylene, propylene and BTX (benzene, toluene and xylene). Crude steel and aluminium production levels are expressed in liquid metal terms.

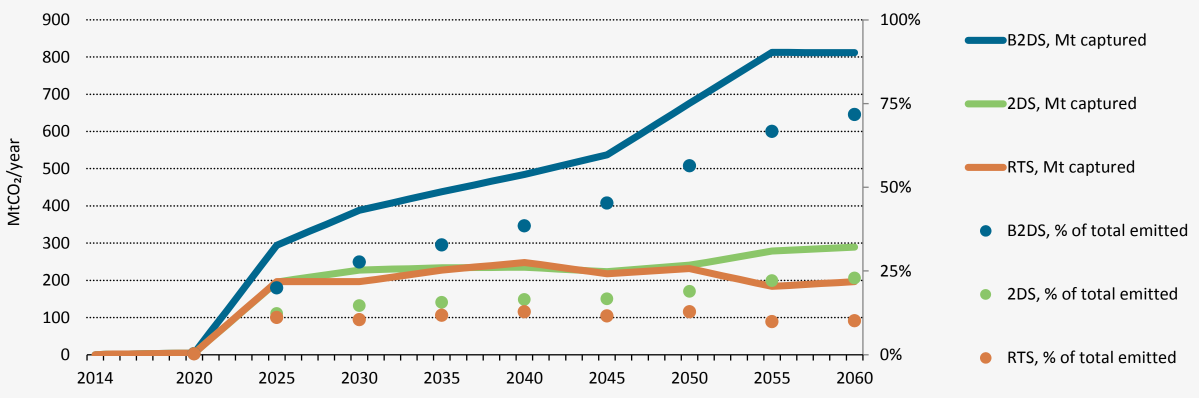
Key point *Production levels are decreased for crude steel, aluminium and primary chemicals in the B2DS due to material efficiency strategies.*

Table 4.1 Material efficiency strategies by subsector and scenario

	RTS	2DS	B2DS
Iron and steel	▪ Post-consumer scrap recycling – continue current trends.	▪ Post-consumer scrap recycling – improved collection rates.	▪ Same strategy as 2DS. ▪ Improved manufacturing and semi-manufacturing yields. ▪ Post-consumer scrap reuse.
Cement	▪ Clinker substitution – continue current trends.	▪ Maximised clinker substitution ratios.	▪ Same strategy as 2DS.

carbon separation processes, which make capture more cost-competitive than other processes. Ammonia production accounts for almost half and methanol production for 29% of CO_2 emissions captured in the chemical subsector in the B2DS.

Figure 4.10. Global CO_2 captured and stored in the chemicals and petrochemicals subsector



Note: CO_2 capture technologies cannot be deployed in the chemicals sector before 2025 in the *ETP* scenarios, except for specific projects already in the pipeline.

Key point *Nearly 75% of CO_2 emitted must be captured by 2060 in the B2DS.*

Utilisation of captured CO_2 for industrial processes is already economical in some applications and could have co-benefits in terms of accelerated development of capture technologies and CO_2 transport infrastructure. Commercial CCU connections between carbon sources and applications could develop infrastructure and capture technology that could then be used in the longer term in combination with permanent storage. In primary chemicals production, CCU accounts for almost 6 $GtCO_2$ by 2060 in the B2DS, of which 97% is carbon capture from CO_2 emissions from ammonia production for making urea.[35]

Of the global cumulative CO_2 captured and stored in the B2DS, 39% is in China and 13% is in the Middle East. Primary chemicals production is expected to double in China and more than double in the Middle East by 2060 from current levels.

High-value chemicals

To reduce CO_2 emissions from chemicals production beyond the recycling and energy efficiency improvement potentials, switching to lower-carbon feedstocks and process routes is an option. For HVC, steam cracking is the most widely established process, mainly using naphtha and ethane as feedstocks (81% of global HVC capacity excluding production in refineries). Several shifts in process routes and feedstocks for HVC production would be driven by CO_2 emissions reductions in the B2DS (Figure 4.11):

- Steam cracking shifts slightly from naphtha-based (32% reduced global HVC production share in the period 2014-60) to ethane-based steam cracking (increased by 82% in the same period) with a lower direct CO_2 footprint. This structural change impacts the resulting

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[35] The *ETP* industry model includes two CCU options in the chemicals and petrochemicals sector: urea and electrolysis-based methanol production. These are driven by established product value chains to mitigate the limitation of lack of geospatial information and as a consequence of the product scope of the model. Other avenues may arise for the commercial use of CO_2, though these are highly dependent on local synergies.

In the longer term, policy makers should guide industrial innovation towards low-carbon options. The progress of environmentally sustainable industry innovation over the next decade will be crucial to enable low-carbon technologies with the best potential to achieve commercial availability to support industry and other sectors' efforts to reach deep carbon emissions reductions. Developing a broad portfolio of low-CO_2 emissions industrial process technologies and products is critical to ensure that enough viable options will be ready in the post-2030 time frame. The 2DS and B2DS highlight cost-optimal pathways given available data and current technology knowledge, but other technologies, including more radical, early-stage options, could play a role as technology evolves and should not be excluded from investigation.

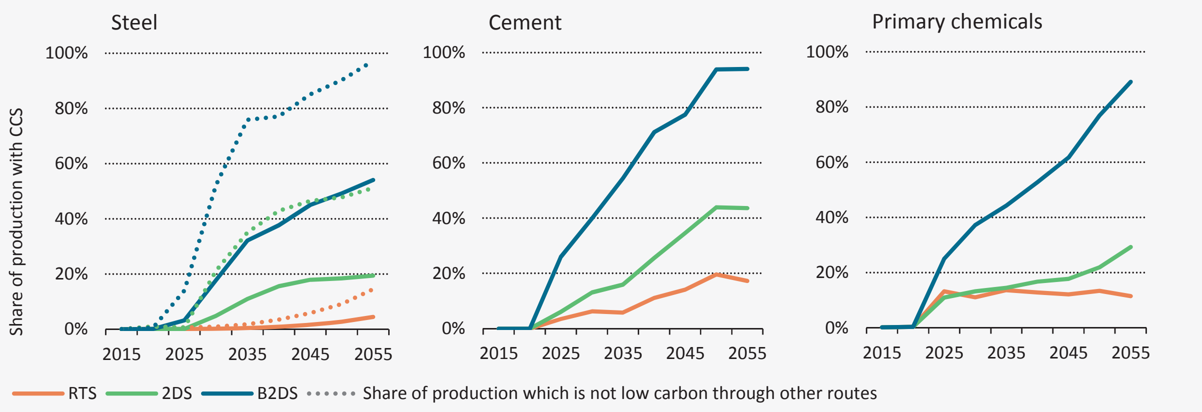
In parallel with process and technology development, governments and industry should work jointly to widely deploy innovative low-carbon industrial processes by facilitating investment while implementing effective mechanisms for broad international technology transfer and capacity building. International public-private collaboration will also be critical in order to strategically identify, design and roll out cost-optimal CO_2 transport and storage infrastructure for CCS to enable the deep carbon emissions reductions necessary in the long term.

Long-term environmental sustainability at the energy system level should be considered from an industrial perspective as well; incentives for implementation of demand-side management strategies, such as energy price schemes that reward low-carbon electricity/thermal exports and flexible imports from the grid, can have significant benefits for the overall energy system. Similarly, integrated assessments of energy demand and mapping of local energy resources and demands are needed to identify cost-effective energy supply strategies. Strategic heating and cooling planning can help to identify cost-effective opportunities for IEH recovery at the local and national levels.

Table 4.2 Policy recommendations to support the low-carbon transition for industry

Focus	Short term	Long term
Tracking progress	■ Improve publicly available statistics. ■ Encourage benchmarking initiatives at the industry subsector level to overcome confidentiality challenges.	■ Set stable long-term targets and choose appropriate indicators to track progress towards those goals.
Energy efficiency and BAT	■ Incentivise implementation of BATs for new capacity additions. ■ Implement and progressively strengthen equipment performance standards. ■ Implement internationally co-ordinated carbon pricing mechanisms. ■ Remove fossil fuel subsidies. ■ Support deployment of energy management systems and energy audits.	■ Continue to incentivise energy efficiency for new processes and technologies. ■ Update benchmarks and targets as BAT improves.
Material efficiency	■ Incorporate price signals into consumer products related to environmental externalities of materials. ■ Encourage reuse prior to recycling. ■ Improve post-consumer scrap collection and recycling. ■ After reuse and recycling, valorise post-consumer waste for energy recovery.	■ Improve post-consumer scrap collection infrastructure in all countries. ■ Encourage R&D for new processes and products that optimise use of industrial materials.

Figure 8.7. Share of CCS in industrial production



Key point *Under the B2DS, CCS is applied to almost all cement and chemicals production, and to almost all steel production that is not low carbon through other routes.*

As well as a large increase in the level of CCS captured in 2060, the B2DS also calls for a much more rapid ramp-up, which reaches a higher penetration in all three sectors in the B2DS than in the 2DS. This emphasises the need for policy that drives capture uptake more quickly, as well as the necessary storage reserves.

Box 8.4. Al Reyadah CCS project

Al Reyadah, a joint venture between Masdar and Abu Dhabi National Oil Company (ADNOC), has developed a project that takes captured CO_2 from the Emirates Steel Factory in Abu Dhabi and transports it to the ADNOC-operated oilfield for the purpose of enhanced oil recovery (EOR) (MIT, 2016).

ADNOC is a United Arab Emirates (UAE) state-owned oil company, and Masdar is a wholly owned subsidiary of the Abu Dhabi government-owned Mubadala Development Company. The project began operations in November 2016.

The project scope includes operation of a greenfield CO_2 compression facility adjacent to the Emirates Steel Factory. CO_2 is transferred at low pressure to the compression facility, where it is dehydrated, compressed, metered and exported to the CO_2 pipeline. The CO_2 is transported 43 km through an eight-inch pipeline for injection into ADNOC reservoirs (GCCSI, 2017c).

The project is the Middle East's first commercial-scale carbon capture, use and storage facility and will sequester up to 800 000 tonnes of CO_2 annually. The engineering, procurement and construction contract for the facility and pipeline was valued at USD 122 million (450 million UAE dirham) (Masdar, 2017).

CCS in fuel production and transformation

In 2060, 1.8 $GtCO_2$ is captured and stored from fuel production and transformation in the 2DS and 2.3 $GtCO_2$ in the B2DS. A significant increase in demand for biofuels is seen in both the 2DS and the B2DS, including biodiesel, hydrogen and ethanol, as they offer an energy source with net-neutral emissions. The combination of CCS and bioenergy allows for the generation of negative emissions. Accordingly, CCS is applied widely to the biofuel production sector, capturing 1.6 $GtCO_2$ in the 2DS and 2.2 $GtCO_2$ in the B2DS.

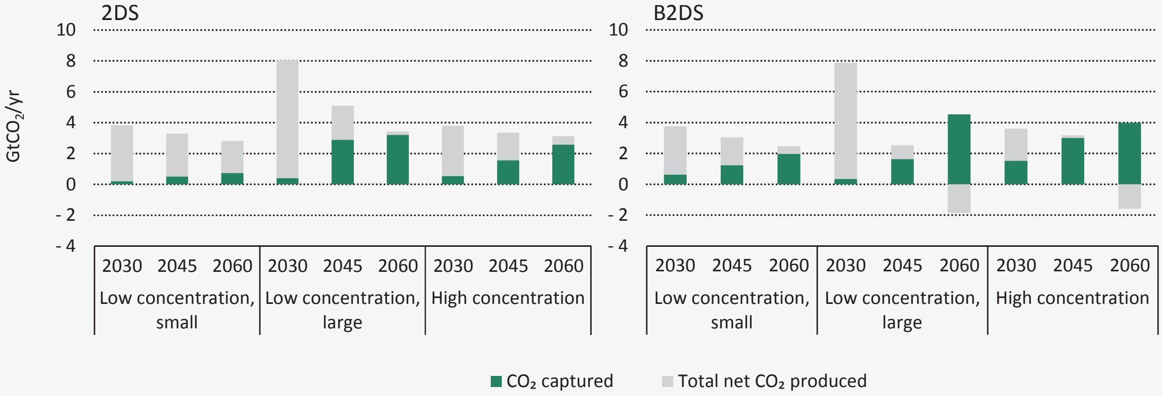
Capturing CO_2 from natural gas and hydrogen production is well understood and an established technology. Many of the early applications of CCS have been in natural gas processing, as the separation of CO_2 is often already an inherent part of the process. Hydrogen production has also been a leader in the early deployment of CCS. Accordingly, these upstream processes account for much of the early CCS activity. In the 2DS, 5% of all CO_2 captured and stored is from natural gas processing in 2025, but by 2060, capture from natural gas production and processing is incidental to total CO_2 captured.

CO_2 capture projects in fuel transformation can drive early investment in CO_2 transport and storage and are among the vanguard of early CCS projects. The technologies involved are well understood and often quite mature. Also, applying CCS in this sector has a lower impact on the competitiveness of facilities, owing to the particular market and pricing dynamics. Furthermore, many of the companies involved in the upstream fuel sector have experience of operating in the subsurface and are therefore more likely to develop the initial storage sites.

Challenges for the deployment of carbon capture in the B2DS

Both the 2DS and the B2DS show a widespread deployment of CCS from industrial and energy-related point sources, which differ according to their size and the CO_2 concentration in their gas streams (Figure 8.8). The B2DS involves more CO_2 capture from small point sources with dilute CO_2 streams (3% to 12% CO_2 by volume) such as industrial boilers, and decentralised co-generation plants (see box 8.5 for a discussion of CO_2 capture technologies).[3] Separating CO_2 from these point sources is often more energy intensive and costly, as the capture equipment benefits less from economies of scale than in the case of large-scale sources. Moreover, creating space for capture equipment around small point sources on cramped industrial sites, such as complex refineries, may increase costs further.

Figure 8.8. CO_2 captured by size and concentration of stream



Note: $GtCO_2$/yr = gigatonnes of CO_2 per year.

Key point *More CO_2 is captured from more expensive, lower-concentration and smaller sources in the B2DS.*

To realise widespread deployment of CCS, as envisaged in the B2DS, technological development is required to reduce the costs of CCS technologies. The necessary conditions

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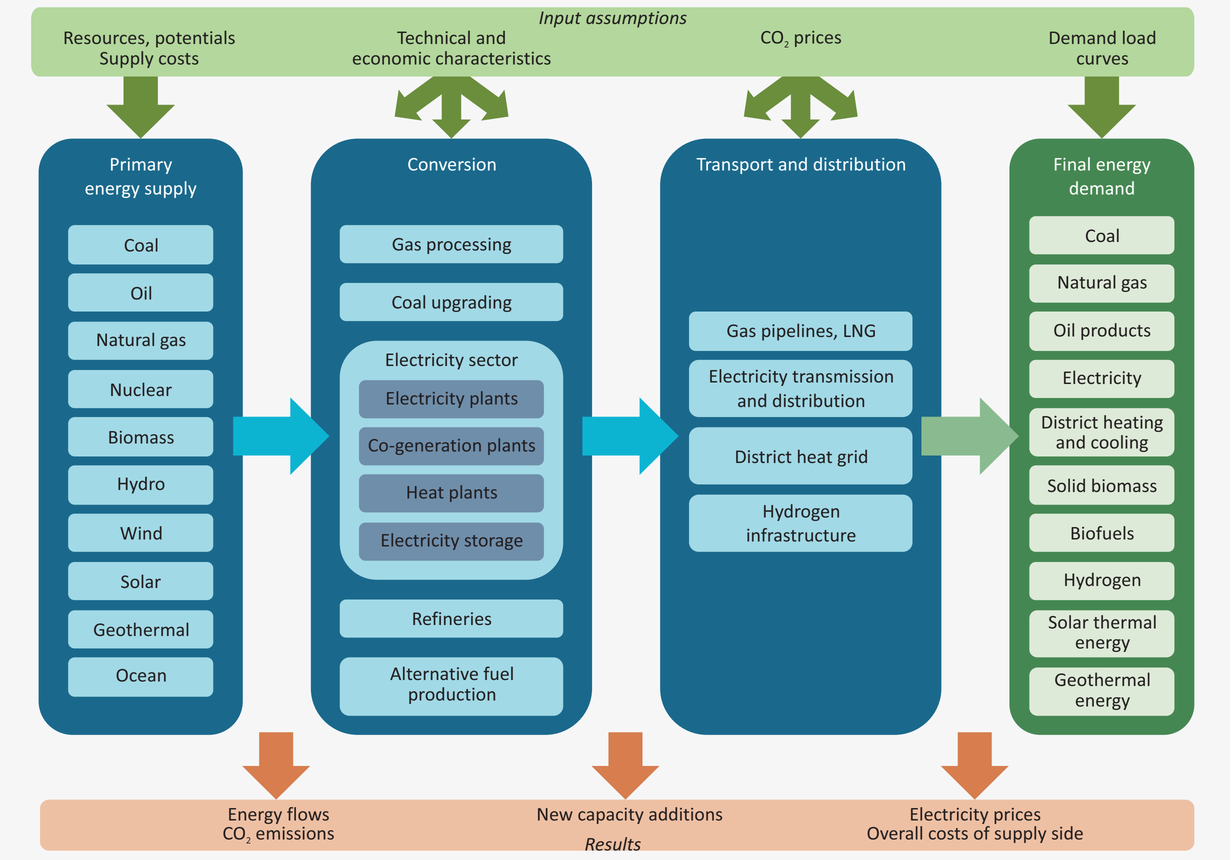
[3] Co-generation refers to the combined production of heat and power.

(TCP)[2] of the International Energy Agency (IEA) and allows an economic representation of local, national, and multiregional energy systems on a technologically detailed basis (Loulou et al., 2005).

The model covers 28 regions, representing either individual countries, such as the People's Republic of China (hereafter, "China") or India, or aggregates of several countries, such as the Association of Southeast Asian Nations (ASEAN). The model regions are linked by trade in fossil energy carriers (crude oil, petroleum products, coal, pipeline gas, or liquefied natural gas [LNG]), biofuels (biodiesel, bioethanol), and electricity.

Starting from the current situation in the conversion sector (e.g. existing capacity stock, operating costs, and conversion efficiencies), the model integrates the technical and economic characteristics of existing technologies that can be added to the energy system. The model can then determine the least-cost technology mix needed to meet the final energy demand calculated in the ETP end-use sector models for agriculture, buildings, industry and transport (Figure A.2).

Figure A.2. Structure of the ETP-TIMES model for the conversion sector



Notes: CO_2 = carbon dioxide; *co-generation* refers to the combined production of heat and power.

Key point *ETP-TIMES determines the least-cost strategy using supply-side technologies and fuels to cover the final energy demand from the end-use sector models.*

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[2] Further information on the TIMES model generator, its applications, and typical energy technology input data assumptions can be found on the ETSAP website at www.iea-etsap.org.

Definitions, regional and country groupings and units

Definitions

	2–, 3– and 4–wheelers	This vehicle category includes motorised vehicles having two, three or four wheels. 4–wheelers are not homologated to drive on motorways, such as all–terrain vehicles. Most often, 2– and 3–wheelers are reported as an aggregated class.
A	Advanced biofuels	Advanced biofuels comprise different emerging and novel conversion technologies that are currently in the research and development, pilot or demonstration phase. This definition differs from the one used for "advanced biofuels" in the US legislation, which is based on a minimum 50% life–cycle greenhouse gas (GHG) reduction and which, therefore, includes sugar cane ethanol.
	Aquifer	A porous, water–saturated body of rock or unconsolidated sediments, the permeability of which allows water to be produced (or fluids injected). If the water contains a high concentration of salts, it is a saline aquifer.
B	Biodiesel	Biodiesel is a diesel–equivalent, processed fuel made from the transesterification (a chemical process which, in this case, refers to the removal of glycerine from the oil) of both vegetable oils and animal fats.
	Bioenergy	Bioenergy is material which is directly or indirectly produced by photosynthesis and which is utilised as a feedstock in the manufacture of fuels and substitutes for petrochemical and other energy intensive products.
	Biofuels	Biofuels are fuels derived from biomass or waste feedstocks and include ethanol and biodiesel. They can be classified as conventional and advanced biofuels according to the technologies used to produce them and their respective maturity.
	Biogas	Biogas is a mixture of methane and CO_2 produced by bacterial degradation of organic matter and used as a fuel.
	Biomass	Biological material that can be used as fuel or for industrial production. Includes solid biomass such as wood, plant and animal products, gases and liquids derived from biomass, industrial waste and municipal waste.

Biomass and waste	Biomass and waste includes solid biomass, gas and liquids derived from biomass, industrial waste and the renewable part of municipal waste. Includes both traditional and modern biomass.
Biomass-to-liquids	Biomass-to-liquids (BTL) refers to a process that gasifies biomass to produce syngas (a mixture of hydrogen and carbon monoxide), followed by synthesis of liquid products (such as diesel, naphtha or gasoline) from the syngas using Fischer-Tropsch catalytic synthesis or a methanol-to-gasoline reaction path. The process is similar to those used in coal-to-liquids or gas-to-liquids.
Bio-SNG	Bio-synthetic natural gas (Bio-SNG) is biomethane derived from biomass via thermal processes
Black liquor	A by-product from chemical pulping processes, which consists of lignin residue combined with water and the chemicals used for the extraction of the lignin.
Bond market/bonds	Bond is a formal contract to repay borrowed money with interest at fixed intervals.
Benzene, toluene and xylene	Benzene, toluene and xylene (BTX), also referred to as aromatics, are a major group of products from the petrochemicals sector.
Buses and minibuses	Passenger motorised vehicles with more than nine seats.
Capacity credit	Capacity credit refers to the proportion of capacity that can be reliably expected to generate electricity during times of peak demand in the grid to which it is connected.
Capacity (electricity)	Measured in megawatts (MW), capacity (electricity) is the amount of power produced, transmitted, distributed or used at a given moment.
Carbon capture and storage	A process in which CO_2 is separated from a mixture of gases (e.g. the flue gases from a power station or a stream of CO_2-rich natural gas) and compressed to a liquid state; transported to a suitable storage site; and injected into a geologic formation where it is retained by natural trapping mechanisms and monitored as necessary.
Clinker	Clinker is a core component of cement made by heating ground limestone and clay at a temperature of about 1 400°C to 1 500°C.
CO_2 emissions	CO_2 emissions in the ETP analysis include, if not noted otherwise, emissions from energy use and process emissions (industry, gas processing). If a fossil fuel is used as a raw material (or feedstock) for manufacture of products such as plastics or in a non-energy use (e.g. bitumen for road construction), only some of the carbon in the fossil fuel is oxidised to CO_2.
Coal	Coal includes both primary coal (including hard coal and brown coal) and derived fuels (including patent fuel,

Regional and country groupings

Africa	Algeria, Angola, Benin, Botswana, Cameroon, Congo, Democratic Republic of Congo, Côte d'Ivoire, Egypt, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Libya, Morocco, Mozambique, Namibia, Nigeria, Senegal, South Africa, South Sudan, Sudan, United Republic of Tanzania, Togo, Tunisia, Zambia, Zimbabwe and other African countries and territories.[1]
ASEAN (Association of Southeast Asian Nations)	Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Myanmar, Philippines, Singapore, Thailand and Viet Nam.
Asia	Bangladesh, Brunei Darussalam, Cambodia, People's Republic of China, India, Indonesia, Japan, Korea, the Democratic People's Republic of Korea, Malaysia, Mongolia, Myanmar, Nepal, Pakistan, Philippines, Singapore, Sri Lanka, Chinese Taipei, Thailand, Viet Nam and other Asian countries and territories.[2]
China	Refers to the People's Republic of China, including Hong Kong.
European Union	Austria, Belgium, Bulgaria, Croatia, Cyprus,[3] Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden and United Kingdom.
Latin America	Argentina, Bolivia, Brazil, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Haiti, Honduras, Jamaica, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Trinidad and Tobago, Uruguay, Venezuela and other Latin American countries and territories.[4]
Middle East	Bahrain, Islamic Republic of Iran, Iraq, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates and Yemen. It includes the neutral zone between Saudi Arabia and Iraq.
OECD	Includes OECD Europe, OECD Americas and OECD Asia Oceania regional groupings.
OECD Americas	Canada, Chile, Mexico and United States.
OECD Asia Oceania	Includes OECD Asia, comprising Japan, Korea and Israel,[5] and OECD Oceania, comprising Australia and New Zealand.
OECD Europe	Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Luxembourg, Netherlands, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey and United Kingdom.
Other developing Asia	Non-OECD Asia regional grouping excluding People's Republic of China and India.

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1. Individual data are not available for: Burkina Faso, Burundi, Cape Verde, Central African Republic, Chad, Comoros, Djibouti, Equatorial Guinea, Gambia, Guinea, Guinea-Bissau, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Niger, Reunion, Rwanda, Sao Tome and Principe, Seychelles, Sierra Leone, Somalia, Swaziland, Uganda and Western Sahara (territory). Data are estimated in aggregate for these regions.

Units of measure

Unit prefix	E	exa (10^{18}, quintillion)
	P	peta (10^{15}, quadrillion)
	T	tera (10^{12}, trillion)
	G	giga (10^{9}, billion)
	M	mega (10^{6}, million)
	k	kilo (10^{3}, thousand)
	c	centi (10^{-2}, hundredth)
	m	milli (10^{-3}, thousandth)
	μ	micro (10^{-6}, millionth)
Area	m^2	square metre
Distance	km	kilometre
	m	metre
	pkm	passenger kilometre
	tkm	tonne kilometre
	vkm	vehicle kilometre
Emissions	tCO_2	tonne of carbon dioxide equivalent
	$GtCO_2$	$GtCO_2$–eq gigatonnes of carbon dioxide equivalent (using 100–year global warming potentials for different greenhouse gases)
	$MtCO_2$	million tonnes of carbon dioxide equivalent
	gCO2/kWh	grammes of carbon dioxide per kilowatt hour
Energy	MBtu	million British thermal units
	MJ	megajoule (1 joule x 10^{6})
	GJ	gigajoule (1 joule x 10^{9})
	TJ	terajoule (1 joule x 10^{12})
	PJ	petajoule (1 joule x 10^{15})
	EJ	exajoule (1 joule x 10^{18})
	GJ/t	gigajoules per tonne
	kWh	kilowatt hour
	MWh	megawatt hour
	GWh	gigawatt hour
	TWh	terawatt hour
	PWh	petawatt hour
	MWh/t	megawatt hour per tonne

	kWh/m^2	kilowatt hour per square metre
	kWh/vkm	kilowatt hour per vehicle kilometre
	kW	kilowatt
	MW	megawatt
	GW	gigawatt
	kV	kilovolt
Mass	t	tonne
	kt	kilotonne
	Mt	million tonnes
	Gt	gigatonne
Temperature	°C	degrees Celsius
Others	bbl	barrel
	Lge	litre of gasoline equivalent
	lm/W	lumens per watt
	mD	millidarcy
	RPK	revenue per passenger kilometre
	Wh/L	watt hours per litre