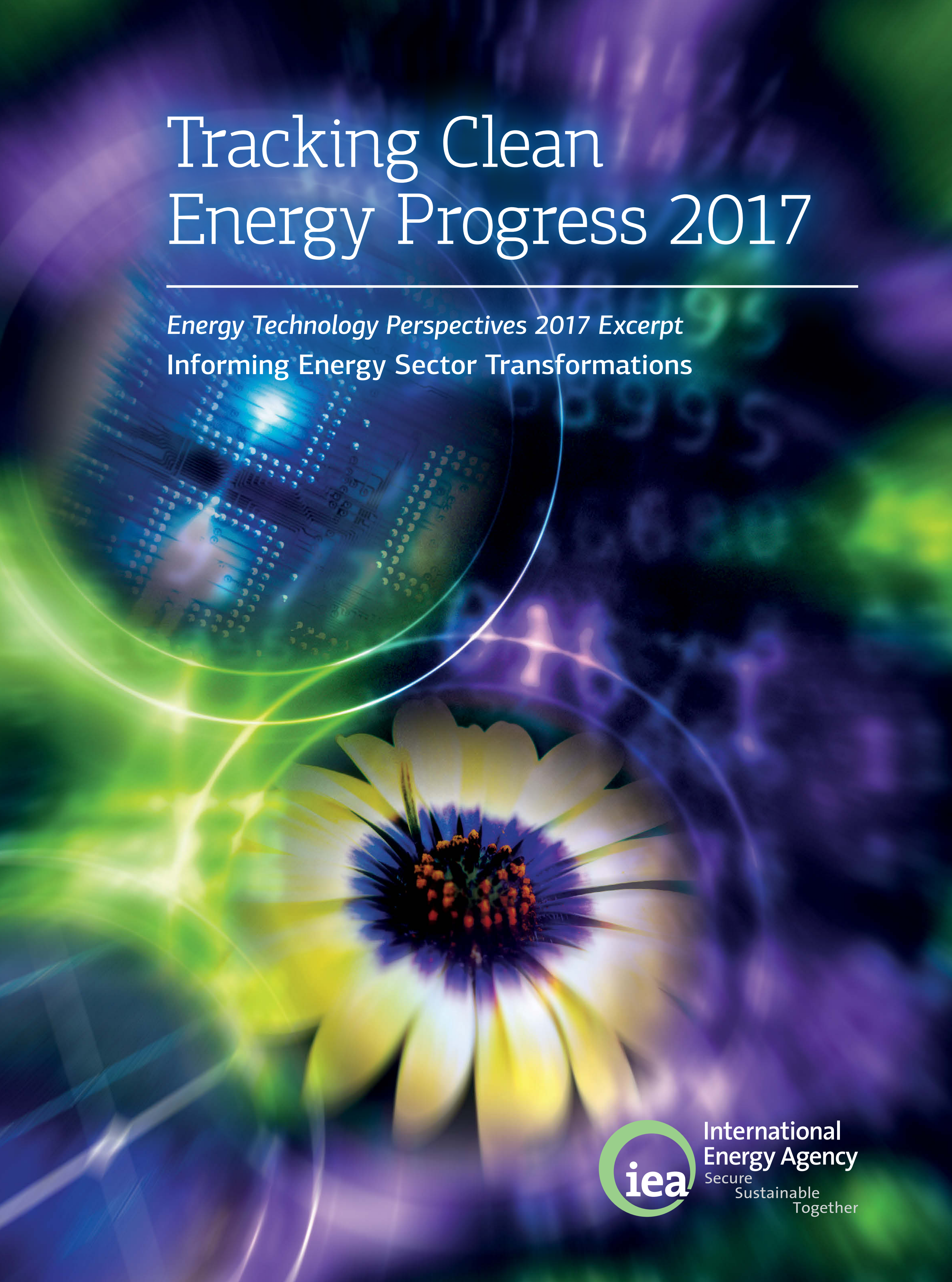
Tracking Clean Energy Progress 2017

Energy Technology Perspectives 2017 Excerpt

Informing Energy Sector Transformations



International Energy Agency
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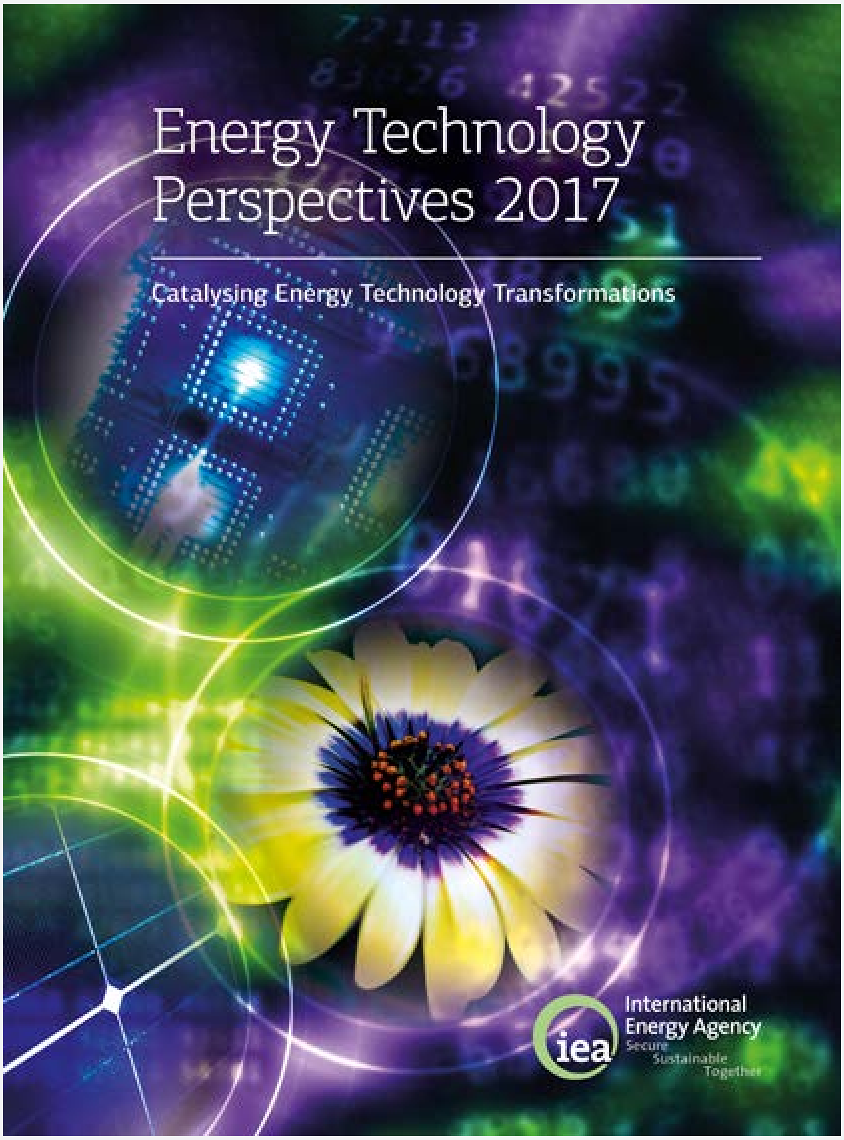

Release 6 June 2017

INTERNATIONAL ENERGY AGENCY

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

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

IEA member countries:

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Belgium
Canada
Czech Republic
Denmark
Estonia
Finland
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Italy
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Netherlands
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The European Commission also participates in the work of the IEA.

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Foreword

Energy systems around the world are undergoing substantial changes. Many of these shifts are being driven by purposeful government policies, whether to put a country on a low-carbon transition path, reduce air pollution, secure energy independence and security, or reduce costs and improve efficiencies. Other changes are being driven by external forces, including broader movements in energy markets or by deep societal transformations such as the increased use of information and communications technologies in every wake of life.

In order to navigate this ever-changing energy landscape, governments, companies, and other stakeholders need information. It is critical to know where we are before knowing where we want to go. What is the existing state of technologies across different parts of the energy sector, where are governments steering their energy systems, what progress is being made and how can their goals be achieved efficiently and cost-effectively?

The IEA *Tracking Clean Energy Progress (TCEP)* provides such a tool, and can help governments, companies, and other stakeholders build cleaner and more sustainable energy systems. Different technologies will of course be more or less relevant in different countries, which is why *TCEP* takes a broad and technology-neutral approach that covers a full range of energy subsectors – from bioenergy to nuclear, from building envelopes to key industries, from solar photovoltaics to carbon capture and storage (CCS).

This year, the report includes a special feature on clean energy innovation, which brings the world's best data on public and private investment in research, development, and demonstration (RD&D) in one place. This should be helpful to all global actors, but especially for those countries involved in Mission Innovation who have pledged to double their clean energy innovation budgets over five years as well as for key private sector actors like the Breakthrough Energy Coalition.

These public and private efforts carry enormous potential to help develop the technologies of tomorrow. These efforts will be critical to help countries achieve the long-term goals of the Paris Agreement on climate change but also to reduce air pollution, bolster energy security and invigorate the economies of tomorrow.

Thanks to its growing family of member and partner governments, wide and deep business partnerships, and unparalleled expert analysts, which includes 6 000 global experts in its Technology Collaboration Programmes, the IEA strives to help the world achieve its energy policy goals – and do so efficiently and effectively.

Progress has been made to ensure that IEA analysis is more accessible, and a new interactive web portal for *TCEP* has been created on the IEA website. It is my hope that *TCEP 2017* is useful in our shared effort to promote sustainable and secure energy systems for the future.

Dr. Fatih Birol
Executive Director
International Energy Agency

Key messages

In 2016, 3 of the 26 tracked technologies were "green", that is, on track toward a sustainable energy transition: more mature variable renewables (onshore wind and solar), electric vehicles, and energy storage. While presently representing only a small share of the total energy system, these technologies are rapidly scaling up and continue to strengthen their position as mainstream energy solutions.[1]

- A new historic record has been reached in the electrification of passenger transportation, with over 750 000 electric vehicles (EVs) sold in 2016, raising the global stock to two million. A slowdown in market growth of 40% in 2016 from 70% in 2015 still maintains EVs on track to reach 2°C Scenario (2DS) levels in 2025, but puts the technology at significant risk of missing the 2020 interim milestone and in turn raises risks toward the 2025 goal.
- Storage technologies continued rapid scale-up in deployment, reaching almost 1 gigawatt (GW) in 2016. These advances were driven by favourable policy environments and reductions in battery prices. Storage technologies are on track with 2DS levels, but reaching cumulative capacity of 21 GW – the 2DS level projected by 2025 – will need further policy action.
- Strong annual capacity growth continued for both solar PV and onshore wind in 2016, with record low long-term contract prices in Asia, Latin America and the Middle East. Prospects for renewable electricity are bright over the medium term, driven by cost reductions and policy improvements in key markets. With only solar PV and onshore wind fully on track, however, renewables overall are still falling short of longer-term 2DS levels, despite a record-breaking 6% overall generation growth in 2016.
- The "on track" status of these three technologies depends on all other technologies also playing their part in the transition, which is not currently the case. If progress in other technologies does not accelerate, this year's on-track technologies may have to progress even more ambitiously to overcompensate for lagging technology areas to ensure the overall energy transition is on track.

Sufficient progress is not being delivered in most other technologies. Fifteen technologies are "orange", that is they are showing advances, but with more effort needed to become "green". On a positive note,

1. See "Technology overview notes" on page 94 for explanation of the data sources used and section "Tracking progress: How and against what?" on page 16 for explanation of scenarios used for tracking.

within these 15 “orange” technologies, 10 showed recent improvements, while only one exhibited recent negative developments.

- Nuclear power saw 10 GW of capacity additions in 2016, the highest rate since 1990. Yet doubling of the 2016 annual capacity addition rate to 20 GW annually is required to meet the 2DS to offset planned retirements and phase-out policies in some countries. Closures of reactors struggling to compete in markets with depressed wholesale electricity prices are also looming, and 2016 brought only 3 GW of new construction starts, posing risks to the future growth rates of nuclear power generation.
- Gas-fired power generation needs to make additional progress to get on track with the 2DS. The last three years of growth above the global 2DS targets of 2.4% offsets the earlier declines in generation and corrects some fragility of the growth path. To stay on track with the sustainable energy transition pathway, additional progress is also needed in efficiency and flexibility performance of plants. This will provide support for the integration of variable renewables and serve as a short-term, lower-carbon alternative to coal, while preventing stranding of assets in the long term.
- Industrial sector action must accelerate to meet the 2DS trajectory and keep annual growth in final energy consumption below 1.2% from 2014 to 2025, less than a half of the average 2.9% annual growth since 2000. While the sector has continued to progress in energy efficiency and low-carbon technology deployment, industrial production growth must be further decoupled from energy use and carbon dioxide (CO_2) emissions.
- In spite of continued positive electrification trends in personal vehicles in 2016, remaining transport modes, including aviation, shipping and road freight show a lack of sufficient progress. A stabilisation is needed in the increasing trajectory of transport sector CO_2 emissions to stay on track with the 2DS targets, shifting from 2.5% annual emissions growth since 2010 to remaining stable from 2015 to 2025 and decreasing rapidly afterwards.

Eight technologies are red, that is, significantly off-track and means that they require renewed policy focus. Only three of these “off-track” technologies saw significant (and promising) recent improvements over the past year.

- Coal continues to dominate global power generation, with a share of over 40% in 2016. Moreover, 30% of new coal power capacity additions in 2015 used low-efficiency subcritical technology. To stay on 2DS track, coal-based CO_2 emissions must decline by around 3% annually to 2025, led by a retirement in the least efficient technologies and a decline in coal generation not equipped with carbon capture and storage (CCS) after 2020.
- A global portfolio of large-scale CCS projects continues to prove its viability across sectors, but the pipeline of projects has effectively stalled due to lack of new investment decisions. Targeted policy incentives to drive large-scale CCS projects forward into deployment are needed to meet the 2DS target of over 400 million tonnes of CO_2 ($MtCO_2$) being stored per year in 2025.
- Advanced biofuels need a 25-fold scale-up in production volumes by 2025 to be on track with 2DS. Numerous first-of-a-kind commercial-scale advanced biofuel plants are increasing their production, but mandates for advanced biofuels or reducing the carbon-intensity of transport fuels are needed to accelerate uptake.

- Nearly two-thirds of countries still do not have building energy codes in place. A similar share of energy-consuming equipment in buildings is not covered by mandatory energy efficiency policies. To meet 2DS targets, average building energy use per person globally needs to fall by at least 10% by 2025, to less than 4.5 megawatt hours (MWh).
- A good potential exists globally for a shift to renewable heat, but the resource remains largely untapped. Heat accounts for more than 50% of final energy consumption and is mainly fossil fuel-based. Growth in renewable heat has been steady but slow, and an increase of 32% would be needed by 2025 relative to 2014 to meet 2DS goals.

Tracking progress in the clean energy transition is essential to assess collective progress toward the Paris Agreement's long-term goals and other political imperatives such as reducing air pollution. Tracking is also critical to aid countries, companies, and other stakeholders as they identify specific ways to further step-up their efforts.

- Detailed information on technology deployment and development is needed. This information can help countries understand and track progress toward their national energy transition goals, and aid in effective national policy-making. It can also help avoid various energy policy objectives working in opposition, ensuring the global energy system moves towards a more secure, affordable and sustainable path.
- The IEA will explore ways to further strengthen its various tracking efforts to provide information useful to underpin domestic policy-making and to better inform collective progress, including for the 2018 facilitative dialogue and regular global stocktake processes under the Paris Agreement. In addition to further strengthening *Tracking Clean Energy Progress (TCEP)*, the IEA will continue improving its energy data and indicators as well as tracking of investment trends.

Robust scaling-up of public and private clean energy RD&D investment is essential to deliver sustained, affordable, and secure energy sector transformation. This year's special feature addresses the scarcity of existing information about current public and private investment patterns, and offers suggestions for improvement going forward.

- The total investment in clean energy RD&D has been USD 27 billion in 2015 but is not yet rising globally. It needs to pick up to be on track for a sustainable energy transition. Public funding of clean energy RD&D, including by certain state-owned enterprises, was over USD 19 billion in 2015. This is significantly higher than combined corporate RD&D expenditure of USD 5.4 billion in 2015 and investment by venture capital funds into start-up clean energy technology companies of around USD 2 billion in 2016.
- Clean energy RD&D has been essential in providing us with the clean technology options of today, and will continue to be important into the future. Public funding is striving to fulfil its prescribed function of supporting technologies that are further from the market or have high development and demonstration costs. Corporate investment into clean energy is growing

but remains a small share of total corporate energy sector R&D, which is dominated by companies active in oil and gas, thermal power, networks and utilities. Venture capital funds, on the other hand, are mostly targeting clean energy.

- Implementation of complementary public and private pledges, such as Mission Innovation and Breakthrough Energy Coalition, can serve as essential springboards to boost clean energy innovation. Such new efforts can benefit from building upon existing collaboration mechanisms such as IEA's Technology Collaboration Programmes.
- Understanding RD&D investment patterns can further enhance the effectiveness of RD&D spending as well as highlight areas for collaboration. Efforts should be undertaken to collect better data on public and private sector RD&D spending, develop and track key performance indicators for priority technologies, and follow clean energy RD&D investment progress in concert with the other key elements of the innovation ecosystem.

Summary of progress

Summary of progress tables evaluate progress in clean energy technology using a traffic-light system to provide a mid-term tracking (colour) and a recent trend indicator (arrow) to evaluate latest developments. The three tables contain 26 technology areas classified by sector and subsector, encompassing the entire energy system. The subsequent 18 sections contain in-depth tracking information.

Table 1.1 Energy supply

Overall on track?	Recent trends
● Not on track ● Improvement, but more effort needed ● On track, but sustained deployment and policies required	↘ Negative developments ~ Limited developments ↗ Positive developments
Renewable power	↗
Over 2010-15, renewable power generation expanded by more than 30%, and it is forecast to grow by another 30% between 2015 and 2020. However, renewable power generation growth needs to accelerate by an additional 40% over 2020-25 to reach the 2DS target.	Renewable power capacity additions broke another record in 2016, with over 160 GW of capacity additions. Renewable electricity generation grew an estimated 6%, representing over half of global power generation growth.
Recommendation for 2017: Accelerate growth of renewable electricity generation through policy improvements focused on both system-friendly deployment and technology development.	
Solar PV and onshore wind	↗
Solar PV and onshore wind electricity generation are expected to grow by 2.5 times and by 1.7 times respectively, over 2015-20. This growth trend is on track with the 2DS target, providing a solid launching pad for the further 2 times increase in solar PV and 1.7 times increase in onshore wind respectively, required over the 2020-25 period.	Strong capacity growth continued for both solar PV and onshore wind, and record-low contract prices were announced in 2016.
Recommendation for 2017: Implement system-friendly solar PV and wind deployment and address market design challenges to improve grid integration of renewables.	
Offshore wind and hydropower	↘
Offshore wind generation has grown fivefold over 2010-15 and is expected to double over 2015-20. However, over 2020-25, offshore wind generation needs to triple to be fully on track with its 2DS target. For hydropower, the trend of capacity and generation growth is expected to slow down over the 2015-20 period compared with the previous five years. To be on track with 2DS 2025 targets, an increase in capacity growth rates is required.	Offshore wind additions in 2016 declined by a quarter year on year (y-o-y). Hydropower additions decreased for the third consecutive year in 2016.
Recommendations for 2017: Ensure timely grid connection of offshore wind plants, and continue implementing policies that spur competition to achieve further cost reductions for offshore wind. Improve market design to better value the system flexibility of hydropower.	

Bioenergy, concentrated solar power (CSP), ocean energy and geothermal ~

Progress in renewable technologies at earlier technology development stages remains behind the performance needed to get on track to reach their 2DS targets.

Generation costs and project risks remain higher than conventional alternatives, preventing faster deployment.

Recommendations for 2017: Devise plans to address technology-specific challenges to achieve faster growth. Strategies could include: better remuneration of the market value of storage for CSP; improved policies tackling pre-development risks for geothermal energy; facilitating larger demonstration projects for ocean technologies; complementary policy drivers for sustainable bioenergy.

Nuclear power ~

The average construction starts over the last decade were about 8.5 GW per year. To meet the 2DS targets, more than a doubling is needed – to over 20 GW per year by 2025.

Nuclear power saw 10 GW of capacity additions in 2016, the highest annual increase since 1990, but the year brought only 3 GW of new construction starts.

Recommendation for 2017: Provide clear and consistent policy support for existing and new capacity that includes nuclear power in clean energy incentive schemes and that encourages its development in addition to other clean forms of energy.

Natural gas-fired power ~

Global natural gas-fired power generation increased by 2.2% in 2014. Organisation for Economic Co-operation and Development (OECD) countries experienced 7.1% growth in 2015 with indications of the continuation of this trend in 2016. Generation growth in non-OECD countries is estimated to have equally remained strong into 2015 and 2016.While this is generally in line with the annual growth rate needed to achieve the 2025 2DS target of 2.4%, recent declines show the fragility of the growth path. Additional progress in also needed in efficiency and flexibility performance of plants to provide support for the integration of variable renewables and serve as a short-term, lower-carbon alternative to coal plants, while preventing long-term stranding of natural gas plants.

Gas-fired power capacity investment declined by 40% y-o-y in 2015 to United States dollars (USD) 31 billion, leading to gas capacity additions of 46 GW.

Recommendation for 2017: Support natural gas-fired power generation as a lower carbon alternative to coal through electricity market mechanisms that establish competitiveness of gas with coal, including carbon pricing and additional support policies, such as maximum emission caps and capacity markets.

Coal-fired power ~

To get on track with the 2DS, emissions from coal power would need to decline on average by 3% per year until 2025. Adding to the challenge, in 2015, new coal capacity additions stood at 84 GW, 25 GW of which was subcritical. Under the 2DS, unabated coal capacity additions would have to slow down, with subcritical technology deployment abandoned altogether.

Global coal generation increased by 0.7% y-o-y in 2014 and continued to dominate global power generation in 2014, with a share of over 40%. Coal generation in 2015 and 2016 is estimated to have decreased, but pronounced regional and annual variations can be found.

Recommendation for 2017: Implement national energy plans and policies to rapidly phase out construction of coal plants using subcritical technology.

Carbon capture and storage	↗
The total potential annual capture rate of existing projects is over 30 $MtCO_2$, but given its current proven rate of 9.3 $MtCO_2$, storage is falling short of meeting the 2DS. Average storage must accelerate to reach over 400 $MtCO_2$ annually to be on track to meet the 2DS in 2025.	The global portfolio of large-scale CCS projects continued to expand, with the first steel plant CCS project and the first bioenergy with carbon capture and storage (BECCS) plant being deployed.
Recommendation for 2017: Strengthen public and private investment in large-scale projects and CO_2 transport and storage infrastructure plans, across jurisdictions where applicable.	

Table 1.2 Energy demand

Overall on track?

- Not on track
- Improvement, but more effort needed
- On track, but sustained deployment and policies required

Recent trends

- ↘ Negative developments
- ~ Limited developments
- ↗ Positive developments

Industry	↗
Decoupling of industrial production from CO_2 emissions is critical to achieve the 2DS targets. Annual growth in CO_2 emissions between 2014 and 2025 needs to be limited to 0.1%, compared to 1.1% in the current pathway, with peaking of industrial CO_2 emissions by 2020.	The industrial sector has continued to progress in energy efficiency and low-carbon technology deployment, limiting its final energy consumption y-o-y growth to 1.3% in 2014. To meet the 2DS, action must accelerate to limit the growth in energy consumption to 1.2% per annum by 2025 and stabilize CO_2 emissions.
Recommendation for 2017: Incentivise energy efficiency improvements through mechanisms facilitating retrofitting of existing capacity and deployment of current best available technologies.	
Chemicals and petrochemicals	↗
Average annual growth in the sector's final energy consumption and direct energy-related CO_2 emissions was 2.3% and 2.6%, respectively, during 2000-14, slowing down mainly by switching to lighter feedstocks made economical by price trends in some regions. This trend towards lower CO_2 emissions feedstocks must be sustained in the long term to bring the sector on track to meet the 2DS. Annual increases in process energy consumption and direct CO_2 emissions must stay below 3.1% and 2.8%, respectively, in spite of considerable production increases.	The chemicals and petrochemicals sector has made progress in shifting towards lower-carbon feedstocks in recent years, driven by price changes in some regions.
Recommendation for 2017: Improve publicly available statistics for the chemicals and petrochemicals sector, so as to robustly track progress and set appropriate targets for emissions reductions.	

Pulp and paper	↗
The sector's energy use has grown only 1% since 2000, despite a 23% increase in paper and paperboard production. However, major reductions in energy use and CO_2 emissions are still needed in the 2DS, with energy use and direct non-biomass CO_2 emissions declining by 0.8% and 17%, respectively, by 2025.	Research and development on innovative low-carbon processes and products, such as deep eutectic solvents, has become a priority for the pulp and paper sector in recent years, which could lead to CO_2 and energy benefits.

Recommendation for 2017: Encourage optimal use of by-products as a substitute for fossil fuels, and incentivise increased recycling of paper products and pulp.

Iron and steel	↗
Global crude steel production in electric arc furnaces (EAFs) grew from 29% in 2010 to 30% in 2014. To meet the 2DS targets, global crude steel production in EAFs needs to grow to 40% by 2025, shifting away from basic oxygen furnaces/open hearth furnaces, with the overall energy demand of the sector declining by 6% and CO_2 emissions declining by 11%.	Despite economic difficulties in some regions, crude steel production in EAFs continues to grow.

Recommendation for 2017: Deploy best available technologies and energy efficiency improvements in existing capacity to meet 2DS goals, including maximising deployment of scrap-based EAF production.

Aluminium	↗
Meeting the 2DS pathways will require continued efforts to improve specific energy consumption (SEC) of both primary and secondary aluminium, as well as improvement of scrap collection and recycling rates and new technologies to mitigate process CO_2 emissions. To stay on track towards 2DS, overall average energy use increase by the aluminium sector needs to be limited to 4.3% per annum by 2025.	World average energy intensities of primary aluminium smelting and alumina refining decreased by 1.9% and 5.3%, respectively, from 2013 to 2014. In 2014, 31% of aluminium was produced from scrap, maintaining nearly the same share as in 2013, despite 6.7% growth in overall production.

Recommendations for 2017: Further incentivise the secondary production of aluminium through increased recycling of all scrap types to significantly decrease the energy and emissions intensity of production. Also, incentivise material efficiency strategies to provide significant CO_2 and energy savings.

Cement	↗
To stay on track towards 2DS, biomass and waste fuels need to reach 12.1% of thermal energy consumption by 2025 in the 2DS, and the overall energy use increase by the sector needs to be limited to 0.5% per annum by 2025.	Thermal energy intensity of cement kilns continues to improve, with the shift toward higher-efficiency dry kilns. Alternative fuels combined, including biomass and waste, contributed about 5.3% of thermal energy consumption in 2014.

Recommendation for 2017: Increase public and private support for RD&D of alternative products, clinker substitutes and process routes to decrease cement production CO_2 emissions in the long term.

Transport	~
Transport emissions grew by 2.5% annually between 2010 and 2015. To reach 2DS targets, the sector's well-to-wheel (WTW) greenhouse gas (GHG) emissions must remain stable from 2015 to 2025 and decrease rapidly afterwards. More specifically, WTW GHG emissions from OECD countries need to decline by 2.1% annually between 2015 and 2025 to reach 2DS targets.	CO_2 emissions from transport are still growing, and the transport measures laid out in the nationally determined contributions (NDCs) to the Paris Agreement are not sufficiently ambitious to reach 2DS targets.

Recommendations for 2017: Increase the ambition of the Energy Efficiency Design Index (EEDI) and expand this framework to also include operational efficiency standards for existing ships. This requires swift action to ensure the adequate collection of data along trading patterns of individual vessels.

Electric vehicles	~
With over 750 000 plug-in electric cars[1] sold worldwide in 2016, a new historic record has been hit in the electrification of personal transportation. The global EV car stock has reached 2 million units in circulation. Policy efforts need to be sustained and reinforced to accelerate wider adoption and ensure that EV deployment will not fall short of 2DS growth rates in the coming years.	Even though EV sales grew by 40% between 2015 and 2016, in line with 2DS objectives, this is a slowdown from the 70% growth observed between 2014 and 2015, suggesting an increasing risk to start diverging from a 2DS trajectory.

Recommendations for 2017: Prioritise financial incentives for purchasing PEVs and the availability of charging infrastructure. Offer local incentives favouring PEVs over conventional cars, such as access to urban areas restricted to conventional cars and preferential parking rates. Use public procurement programmes for vehicle fleets to support PEV uptake and support RD&D efforts aiming to reduce battery costs and improve performances.

Fuel economy of light-duty vehicles	↘
Progress in improving the average tested fuel economy of light-duty vehicles (LDVs) has slowed in recent years, from an annual rate of 1.8% in 2005-08, to 1.2% in 2012-15 and only 1.1% in 2014-15. To stay on track with the 2DS, this trend must be reversed, and an annual fuel economy improvement rate of 3.7% through 2030 must be achieved.	Globally, the average rate of fuel economy improvements has slowed in recent years to only 1.1% in 2014-15.

Recommendations for 2017: Introduce fuel economy regulations, starting from labels and consumer information, developing fuel economy baselines and setting fuel economy improvement targets in countries that do not yet have them in place. Strengthen regulatory policies in countries where they already exist, spelling out ambitions for the long term. Make sure that annual improvement rates are compatible with long-term ambitions that match the Global Fuel Economy Initiative (GFEI) goal. Adopt supporting policy tools, including differentiated taxation and low-interest loans, also targeting second-hand vehicles traded between developed and developing countries.

1. See an explanation of the scope and definition of "plug-in electric car" and "EV" in the "Electric Vehicles" section.

Trucks/heavy-duty vehicles	~
Countries with vehicle efficiency standards account for just over half of new heavy-duty vehicle (HDV) sales worldwide. The resultant 10% annual improvement in truck fuel economy over the coming decade is insufficient to counterbalance emissions growth due to increasing trucking activity. To attain 2DS goals, annual WTW GHG emissions growth of heavy-duty trucks must be capped at 1.75% between 2015 and 2025.	Heavy-duty vehicle efficiency and GHG standards have only been recently implemented in Canada, the People's Republic of China (China), Japan and the United States. Nowhere else do such standards exist, but they would need to be adopted more broadly to achieve 2DS goals.

Recommendations for 2017: Develop vehicle efficiency and/or GHG standards for new HDV sales in major markets that do not yet apply them (e.g. Association of Southeast Asian Nations [ASEAN], Brazil, the European Union, India, Korea, Mexico, South Africa, etc.). Better data collection on truck operations is also needed to exploit opportunities to improve systems and logistics efficiencies.

International shipping	~
Meeting the 2DS requires the global shipping fleet to improve its fuel efficiency per vehicle-km at an annual rate of 2.3% between 2015 and 2025. Yet, the Energy Efficiency Design Index (EEDI) of the International Maritime Organization (IMO), applying to new ships only results in a fleet average improvement of 1% to 2025.	The IMO has made progress in agreeing on regulations on reducing sulphur oxide (SOx) and nitrogen oxide (NOx) emissions from ships. Yet its GHG policy is still under consideration: an initial GHG strategy is expected by 2018, which will be a stepping stone to the final strategy expected by 2023. Implementing IMO's final GHG strategy only by 2023 will have very little impact on the possibility of meeting 2025 2DS targets.

Recommendations for 2017: Strengthen enforcement mechanisms for emissions from ships and the EEDI, including inspections, sanctions and legal frameworks, to ensure compliance with IMO measures. Stimulate the engagement of ports in encouraging GHG reductions in ships, e.g. with bonus/malus schemes supporting clean ships from fees applied to ships with poorer environmental performances. Introduce carbon taxes on shipping fuels based on their life cycle GHG emissions.

Aviation	~
Recent annual average fuel efficiency improvements of 3.7% have exceeded industry aviation targets. Yet, with few alternatives to fossil fuels, aircraft efficiency needs to continue to improve at a rapid rate, and incremental shares of advanced biofuels need to be adopted, to be in line with 2DS targets. The WTW GHG emissions of the aviation sector are expected to grow at a rate of 2.0% per year from 2015 to 2025. However, to align with the 2DS emissions must stabilise by 2025 and rapidly decrease afterwards.	The pace of improvement required for the recently proposed CO_2 standard by the International Civil Aviation Organization (ICAO) for new aircrafts falls short of 2DS targets.

Recommendations for 2017: Introduce carbon taxes on aviation fuels based on their life cycle GHG emissions. Align the ambition of ICAO CO_2 standard with the sectorial mitigation targets (carbon-neutral growth by 2020, 2% annual efficiency improvement to 2050, and halving of emissions by 2050 compared with 2005) and clarify the magnitude of the emission savings expected from the recently adopted Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).

Transport biofuels ↗

Conventional biofuels are generally on track to meet 2DS requirements by 2025. However, over 57 billion litres of advanced biofuels are required by the 2DS in 2025. Based on forecasted advanced biofuel production growth to 2020, rapid commercialisation will be necessary over 2020-25 to deliver a twenty-five-fold scale-up in output to stay on track with the 2DS.

Global biofuel production increased by 2% in 2016, a significantly slower rate than pre-2010 levels. However, policy support for advanced biofuels is growing, including the announcement of advanced biofuel mandates in an increasing number of European countries.

Recommendation for 2017: Enhance advanced biofuel policies, including mandates, frameworks limiting the life-cycle carbon intensity of transportation fuels, and financial de-risking measures for advanced biofuel plant investment while costs remain high.

Buildings ↗

Global average building energy use per person since 1990 has remained constant at 5 MWh per person per year. This rate would need to decrease to less than 4.5 MWh per person by 2025 to be in line with 2DS targets. Furthermore, current investments in building energy efficiency are not on track to achieve the 2DS targets.

Average global building energy intensity per square metre only improved by 1.3% last year, while total floor area grew by 3%. Progress in some countries is promising, but overall, buildings are still not on track to meet 2DS objectives by 2025.

Recommendation for 2017: Countries can take immediate action to put forward commitments for low-carbon and energy-efficient buildings to implement their NDCs as a first step and a clear signal to scale up actions across the global buildings sector.

Building envelopes ~

Global annual average building envelope energy intensity improvements of 1.4% have been achieved since 2010. Building envelope intensities need to improve by 30% by 2025 to keep pace with growth in floor area and the demand for greater comfort.

Progress on building energy codes in developing regions last year is a positive step toward 2DS ambitions, but two-thirds of countries still do not have mandatory building energy codes in place.

Recommendation for 2017: Global cooperation should seek to ensure that all countries implement and enforce building energy codes and standards for both new and existing buildings, with improvement in enforcement and verification of codes and standards to overcome barriers to their implementation.

Lighting, appliances and equipment ↗

Electricity consumption by lighting, appliances and building equipment needs to halve from the current 3% average increase per year over the last decade to a 1.5% annual increase in the 2DS.

The growing shift to light-emitting diodes (LEDs) in the last two years is encouraging, with LEDs representing 15% of total residential lamp sales in 2015 (expected to have grown to nearly 30% in 2016). Effort is needed in markets everywhere to ensure that progress carries over to high-performance appliances and equipment.

Recommendation for 2017: Countries should seize on momentum under the recent Kigali Agreement to rapidly move global markets for cooling equipment to much higher energy performances.

Table 1.3 Energy integration

Overall on track?

- Not on track (red)
- Improvement, but more effort needed (orange)
- On track, but sustained deployment and policies required (green)

Recent trends

- ↘ Negative developments
- ~ Limited developments
- ↗ Positive developments

Renewable heat (not on track)		~
	The direct use of renewables for heat (efficient biomass, solar thermal and geothermal) increased by 8% from 2010 to 2014. Renewable heat use remains largely unexploited, in spite of its promising potential. An increase in the consumption of direct renewables for heat by 32% is needed by 2025 to meet the 2DS. For solar thermal, heat production would have to triple by 2025, requiring doubling of the current annual deployment rate.	Renewable heat has seen some growth in recent years but at a much slower rate than for renewable electricity.
	Recommendation for 2017: Governments should set targets and develop strategies for heat decarbonisation that cover all sectors and consider the appropriate balance between renewable heat deployment, heat electrification and energy efficiency improvement.	
Energy storage (on track)		↗
	Energy storage deployment is on track with 2DS due to positive market and policy trends, but an additional 20 GW of capacity is needed by 2025. To remain on track with the 2DS targets, technology deployment will need to continue at its current growth trajectory and grow twenty-fold over the next decade.	Deployed storage reached 930 megawatts (MW) in 2016, with remarkable year-on-year growth of over 50% for non-pumped hydro storage.
	Recommendation for 2017: Clarify the position of storage in the different steps of the electricity value chain to enhance systems-friendly deployment of energy storage and improve business cases for the use of storage in vertically-integrated markets.	

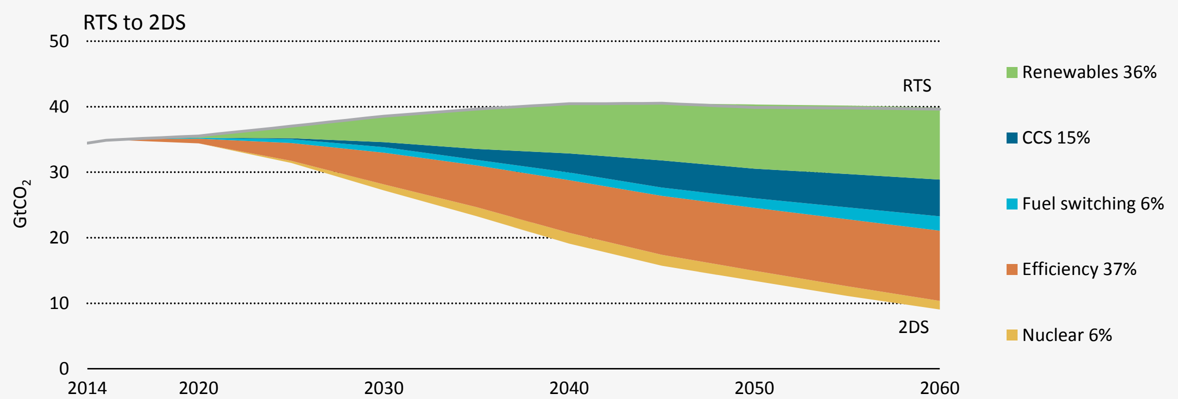
Tracking progress: How and against what?

Published annually, *Tracking Clean Energy Progress (TCEP)* examines the progress of a variety of clean energy technologies. For each, TCEP identifies key measures to further scale up and drive sectors to achieve a more sustainable and secure global energy system.

TCEP uses interim 2025 benchmarks set out in the IEA 2DS, as modelled in *Energy Technology Perspectives 2017 (ETP 2017)* (Box 1.1), as well as the milestones identified in the IEA Technology Roadmaps to assess whether technologies, energy savings and emissions reduction measures are on track to achieve the longer-term 2DS objectives by 2060. *TCEP* evaluates whether a technology or sector is on track (green), needs further improvement (orange) or is not on track (red) to meet 2DS targets. Where possible, this "traffic light" evaluation provides a quantitative metric to track performance. The most recent trend for each technology is highlighted with arrows and tildes and relevant descriptions. An evaluation is also made of past trends.

The report is divided into specific technology or sector sections, and uses graphical overviews to summarise the data behind the key findings. The 2DS relies on development and deployment of lower-carbon and energy-efficient technologies across the power generation, industry, transport and buildings sectors (Figure 1.1).

Figure 1.1. Sector contribution to emissions reduction



Note: $GtCO_2$ = gigatonnes of carbon dioxide.

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

For each technology, *TCEP* examines recent sectoral trends, the latest technology developments and current policy ambition to determine progress against meeting low-carbon technology development pathways. Using a multitude of metrics, *TCEP* provides this analysis under the headings of recent trends, tracking progress and recommended actions.

Tracking overall progress: for each technology, the progress towards 2DS objectives is evaluated, and forward-looking indicators of progress needed to 2025 are provided.

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

- Technology penetration evaluations include: What is the current rate of technology deployment? What share of the overall energy mix does the technology represent?
- Market creation examines: What mechanisms are in place to enable and encourage technology deployment, including government policies and regulations? Where relevant, what is the level of private-sector involvement in technology progress through deployment?
- Technology development discusses: Are technology reliability, efficiency and cost evolving, and if so, at what rate? What is the level of public and private investment for technology RD&D?

Recommended actions: Policy measures, practical steps and other actions required to overcome barriers to 2DS objectives are identified. A specific "recommendation for 2017" is highlighted as a recommendation for the year for each sector or each technology in summarising progress and is based on findings in technology sections.

Box 1.1. Scenarios in *ETP 2017*

The *ETP* model comprises four interlinked technology-rich models that cover the energy supply, buildings, industry, and transport sectors. Depending on the sector, the modelling framework includes 28 to 39 world regions or countries. *ETP 2017* covers the period to 2060, expanding the analysis beyond the 2050 time-frame of previous *ETP* publications.

The *ETP* scenarios are constructed using a combination of forecasting to reflect known trends in the near term and "backcasting" to develop plausible pathways to a desired long-term outcome. The *ETP* scenarios are complementary to those explored in the IEA *World Energy Outlook (WEO).**

The **2°C Scenario** (2DS) lays out an energy system pathway and a CO_2 emissions trajectory consistent with at least a 50% chance of limiting the average global temperature increase to 2°C by 2100. Annual energy-related CO_2 emissions are reduced by 70% from today's levels by 2060, with cumulative emissions of around 1 170 Gt CO_2 between 2015 and 2100 (including industrial process emissions). To stay within this range, CO_2 emissions from fuel combustion and industrial processes must continue their decline after 2060, and carbon neutrality in the energy system must be reached before 2100. The 2DS continues to be the *ETP* central climate mitigation scenario, recognising that it represents a highly ambitious and challenging transformation of the global energy sector that relies on a substantially strengthened response compared to today's efforts.

Other *ETP 2017* scenarios might be mentioned as a point of comparison, but are not used for tracking. The **Reference Technology Scenario** (RTS) takes into account today's commitments by countries to limit emissions and improve energy efficiency, including the NDCs pledged under the Paris Agreement. The RTS requires significant changes in policy and technologies in the period to 2060, as well as substantial additional cuts in emissions thereafter, resulting in an average temperature increase of 2.7°C by 2100.

The **Beyond 2°C Scenario (B2DS)** explores how far deployment of technologies that are already available or in the innovation pipeline could take us beyond the 2DS. Technology improvements and deployment are pushed to their maximum practicable limits across the energy system in order to achieve net zero emissions by 2060 and to stay net zero thereafter, without requiring unforeseen technology breakthroughs or limiting economic growth. This "technology push" approach results in cumulative emissions from the energy sector of around 750 gigatonnes (Gt) between 2015 and 2100, which is consistent with a 50% chance of limiting average future temperature increases to 1.75°C.

* The RTS aligns with the *WEO* New Policy Scenario (NPS) and the 2DS with the *WEO* 450 Scenario.

Tracking clean energy progress and the Paris goals

The Paris Agreement was a historic milestone and establishes various processes to evaluate progress towards emission goals. IEA is well placed to leverage its various tracking activities to provide a comprehensive picture of energy system transformation and to help assess collective progress towards multiple energy policy objectives, including the Paris Agreement's long-term goals. Such metrics and tracking can help inform countries as they consider additional efforts and policies, and the impacts of certain decisions on a multitude of objectives.

Under the Paris Agreement, a common "transparency framework" is being developed to help track progress toward, and achievement of, countries' Nationally Determined Contributions (NDCs). The Agreement also establishes a 2018 Facilitative Dialogue and subsequent Global Stocktakes to assess progress toward collective long-term goals, including the well below 2°C temperature objective. Finally, it encourages countries to develop long-term low-emissions development strategies to guide domestic policy making. IEA energy data and indicators, low-carbon technology tracking through the *TCEP*, and tracking of investment trends could all contribute to the 2018 Facilitative Dialogue and regular Global Stocktake processes.

A keyword search of NDCs for 189 countries in 2017 shows that 188 NDCs mentioned energy, 168 energy efficiency, 147 renewable energy, 10 nuclear power and 11 CCS[1] 35 countries set specific NDC goals framed in terms of energy metrics, with all of them including targets for renewable energy or clean energy supply, while 15 also set energy efficiency or energy demand targets.

Tracking energy system transformation will be essential for understanding progress and priorities related to both national and global GHG mitigation goals. This tracking will require metrics relevant to different sectors, time frames (short- to long-term) and levels (aggregated metrics for outcomes, detailed metrics for drivers of energy sector change) (see Box 1.2). Information across a wide suite of metrics will also help countries develop NDCs that are consistent with global long-term temperature objectives as called for in the Paris Agreement,[2] and with their national mid-century, long-term low-GHG emission development strategies. It will also help ensure that these NDCs are compatible with a multitude of other objectives, such as energy security and economic development.

Metrics are useful not only to monitor action, but also to help inform future decisions; how goals are expressed can influence the policies chosen to implement them, and how ambitiously they are applied. Meeting the Paris temperature goals implies tight constraints on emissions budgets even over the short term. In the 2DS, 38% of the CO_2 budget to 2060 is expected to be used up by 2025, which means that short-term measures play a very important role. Certain short-term actions, such as investments made today in long-lived infrastructure (e.g. buildings and power plants) may not significantly affect GHG emissions over the NDC time period, but will be significant drivers of emissions in the long term. This point is also true for actions taken today that may bring down the cost and improve the performance of key low-carbon technologies over the long term (e.g. RDD&D).

1. UNEP, 2017.
2. Each country's NDC is meant to "be informed by the outcomes of the global stocktake" of progress toward the Agreement's long-term goals (Article 4.9).

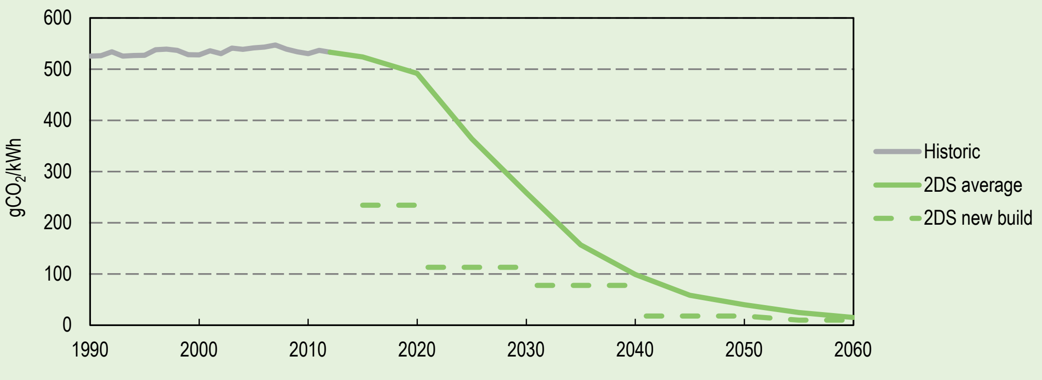
Energy metrics can thus provide policy makers and investors with guidance on the means to achieve long-term emissions pathways consistent with multiple energy policy goals, and the immediate policy priorities that underpin them. Many important metrics fall outside the NDC tracking that will formally occur through the Paris Agreement transparency framework, but will be particularly important for the five-year collective stocktakes of progress to better inform the next round of NDCs, and for countries' long-term low-emissions development strategies.

In the near term, IEA tracking and metrics could play an important role in the Facilitative Dialogue, a collective assessment of progress toward the Paris Agreement's long-term goal taking place in 2018. Occurring before NDCs take effect in 2020, metrics used to inform the dialogue could facilitate revision of 2030 NDC targets and improve the consistency of short-term actions in NDCs with long-term goals. Equally, metrics can provide useful information regarding the benefits of sustainable energy transition for other objectives, including energy security, energy affordability or air pollution.

Box 1.2. Tracking energy sector transformation: Outcomes and drivers

A small number of high-level energy indicators can provide an integrated view of progress and trends across the energy sector, identifying the essential drivers as well as the outcomes of energy sector change. For instance, the CO_2 intensity of new-build electricity plants is a driver metric, while the average CO_2 intensity of electricity generation is an outcome metric. The average carbon intensity of new power capacity declined 27% since 2005 (IEA, 2016d), but needs be at around 100 grammes of CO_2 per kilowatt hour (gCO_2/kWh) in 2025, requiring further steep reduction. The global fleet average emissions intensity of power generation in 2DS needs to be reduced from the current level of 524 gCO_2/kWh to close to zero gCO_2/kWh in 2060 (Figure 1.2). Metrics should comprehensively track changes in both energy production (e.g. oil, gas, electricity) and use (e.g. in buildings, transport and industry).

Figure 1.2 Global fleet average and new-build plants emissions intensity in 2DS



Key point: Tracking of different types of indicators is needed to understand both current status and future trends.

Outcome metrics will be essential for the global stocktake of collective progress towards the Paris Agreement goals, because they can effectively track the overall state of the energy system. However, a broader set of indicators is needed to understand energy sector evolution and to support sound domestic policy. Tracking driver metrics for specific sectors or technologies can pinpoint where progress is needed and inform policy decisions. *TCEP* employs a multitude of metrics to examine recent sectoral trends, the latest technology developments and current policy ambition to determine progress in meeting low-carbon technology development pathways. The *ETP* analytical framework offers a long-term outlook on potential technology choices that are available to ensure delivery of the Paris Agreement goals. Tracking energy sector investment also enables an assessment of short-term actions' consistency with long-term goals. The *World Energy Investment* report examines this leading indicator of the energy transition: the investment analysis of capacity installed in a given year indicates the shape of the energy system to come.

Tracking Clean Energy Progress

Renewable power

● Improvement needed
↗ Positive developments

Renewable power capacity additions continued to reach new record highs in 2016, driven by cost reductions and policies aimed at enhancing energy security and sustainability and improving air quality. According to the IEA *Medium-Term Renewable Energy Market Report 2016*, onshore wind and solar PV are expected to drive the majority of renewable capacity growth over the next five years. They are also the only two technologies on track to reach 2DS targets. Accelerated action is needed to address both policy- and technology-specific challenges for renewables to be firmly on track with the 2DS target.

Recent trends

In 2016, global renewable electricity generation grew by an estimated 6% and represented around 24% of global power output. Hydropower remained the largest source of renewable power, accounting for around 70%, followed by wind (16%), bioenergy (9%) and solar PV (5%). In 2015, net additions to grid-connected renewable electricity capacity reached a record high at 153 GW, 15% higher than in 2014. For the first time, renewables accounted for more than half of new additions to power capacity and overtook coal in terms of world cumulative installed capacity.

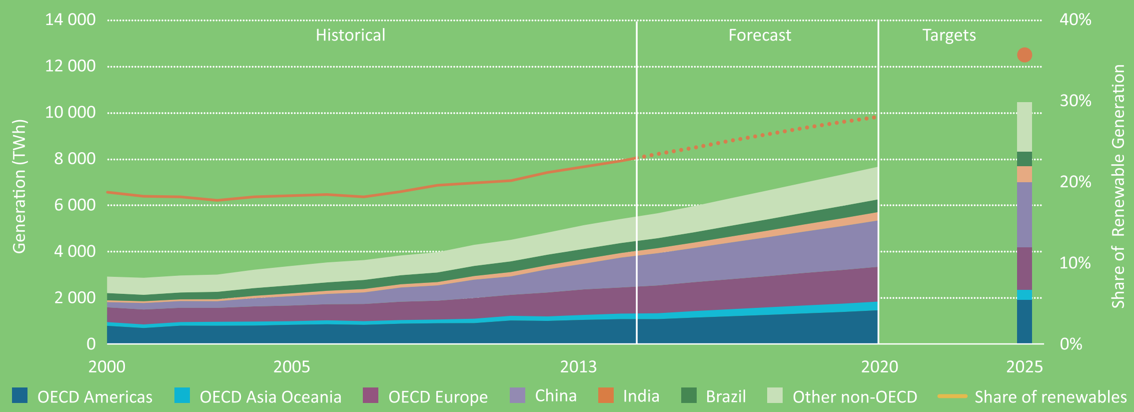
In 2016, solar PV annual additions surpassed that of wind, breaking another record, with 70 GW to 75 GW coming on line, almost 50% higher growth versus 2015. Annual grid-connected solar PV capacity in China more than doubled in 2016 versus 2015, with 34.5 GW becoming operational. Developers rushed to connect their projects before feed-in tariffs (FiTs) were reduced as planned in August 2016. In the United States, solar PV annual additions doubled, with over 14 GW coming on line in 2016, followed by Japan (7.5 GW). The European Union's annual solar PV market contracted by a third to 5.5 GW in 2016 as growth slowed in the United Kingdom. India's annual solar PV additions doubled, with 4 GW added to the grid last year.

In 2016, onshore wind capacity grew by 50 GW, about 15% less versus 2015. This decline was mainly due to China, which connected 19 GW of new onshore wind capacity, significantly less than 32 GW in 2015, when developers rushed to complete their projects to benefit from higher FiTs. However, despite slower capacity growth, China curtailed around 50 terawatt hours (TWh) of wind power last year, with average nationwide curtailment rate increasing from 15% in 2015 to around 17% in 2016. The European Union added over 11 GW, led by Germany and France, followed by the United States (8.2 GW), India (3.6 GW) and Brazil (2.5 GW). In 2016, global offshore wind new additions are estimated to have declined versus 2015 by a third, with annual grid-connected capacity decreasing by about half in Europe as a result of a lull in the United Kingdom and Germany project pipelines.
Hydropower additions are estimated to have decreased for the third consecutive year since 2013, with fewer projects becoming operational in China (12.5 GW). Brazil added almost 5 GW of new capacity. In 2016, CSP capacity grew by almost 0.3 GW, driven almost entirely by Africa. Phase 1 of Morocco's NOOR Ouarzazate Plant, a 160 MW parabolic trough plant with three hours of storage, came on line, while South Africa commissioned two plants.

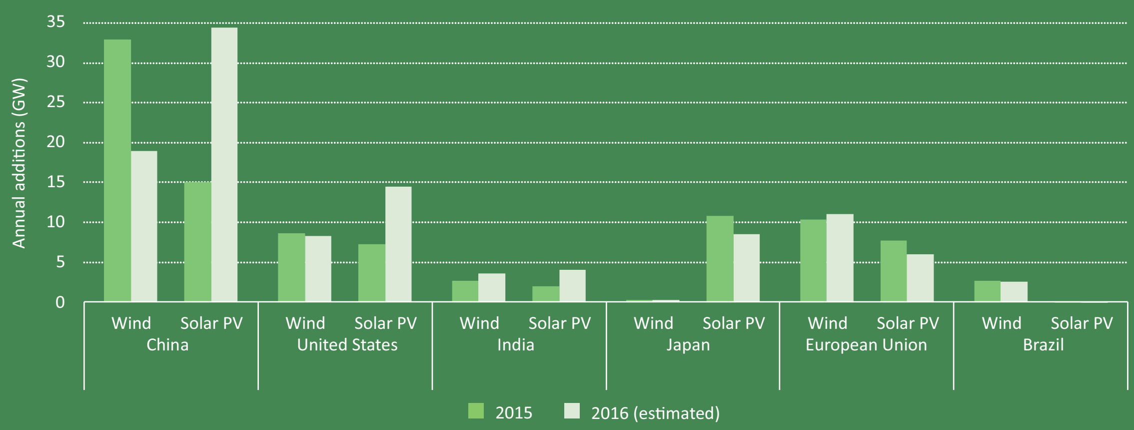
Over the last year, renewable policies for utility-scale projects continued to shift from government-set tariffs to competitive tenders with long-term power purchase agreements. By 2016, almost 70 countries had employed auction/tender schemes to determine support levels, compared with fewer than 20 in 2010. While the first adopters were primarily emerging economies (Brazil and South Africa), this trend has now spread to mature renewable markets (the European Union and Japan). Tender schemes have become a preferred policy option, because they combine competitive pricing with volume control and can support a cost-effective deployment of renewables. As a result, record low prices were announced over the last year in markets as diverse as Latin America, Europe, North America, Asia and North Africa.

In Chile and the United Arab Emirates, solar PV developers signed contracts for projects at below USD 30/MWh, a global record low. In Mexico's energy auctions, winning bids ranged from USD 28/MWh to USD 55/MWh for both solar PV and onshore wind. In India, solar PV contract prices decreased on average by more than a third to USD 55/MWh in 2016 versus 2015/14. For offshore wind, record low contracts were signed in the Netherlands (USD 55/MWh to USD 73/MWh) and Denmark (USD 65/kWh) for a near-shore project, excluding grid connection costs. These contract price announcements reflect a subset of

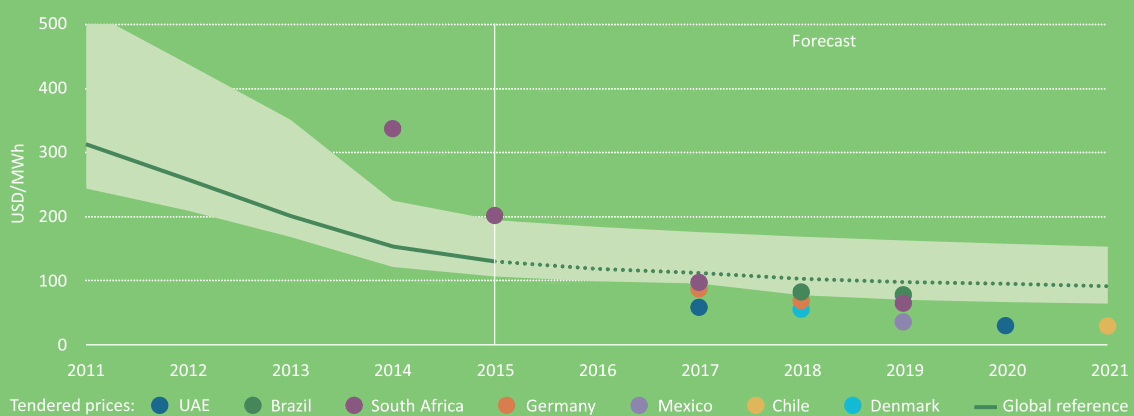
1 Total renewable power generation by region



2 Wind and solar PV annual additions 2015 and 2016 (estimated)



3 Solar PV LCOE and contract prices



projects that are expected to be commissioned over 2017-20 and should not be directly compared to average generation costs that indicate higher values. Still, they signal a clear acceleration in cost reductions, increasing the affordability and improving the attractiveness of renewables among policy makers and investors.

Tracking progress

Renewable power is forecast to grow by 36% over 2015-21, making it the fastest-growing source of electricity generation globally. Generation is expected to exceed 7 650 TWh by 2021, but needs to accelerate further and expand by an additional 26% over 2021-25 for renewables to be firmly on track to reach the 2DS target of 10 300 TWh.

Solar PV and onshore wind are the only two renewable power technologies that are on track to reach their 2DS targets by 2025. Electricity generation is forecast to triple for solar PV and double for onshore wind over five years, driven by strong policy support and further cost reduction expectations. This growth is driven by China, with higher targets announced under China's 13th Five-Year Plan (FYP), and the United States with the multi-year extension of federal tax credits combined with continued supportive policy environment at the state level. India's solar PV growth is also expected to accelerate driven by auctions; however, challenges concerning grid integration and the financial health of utilities hamper a faster growth towards the country's ambitious renewable targets. In Europe, the growth of both solar PV and onshore wind is expected to slow as incentive reductions, policy uncertainties at the country and EU level, and overcapacity remain challenges.

Offshore wind's progress towards the 2DS targets has improved as countries in the European Union are fully on track to reach their 2DS generation targets driven by technology improvements and faster-than-expected cost reductions and grid connection improvements. In addition, the deployment is forecast to accelerate in China with improving economic attractiveness. Hydropower also needs improvement to reach its 2DS generation target. Overall, hydropower new capacity additions are expected to slow over 2015-21 compared with the previous six years owing to the large influence of China's slowdown in large-scale project development due to increasing environmental and social concerns. However, large hydropower growth is forecast to be robust in emerging markets in Southeast Asia, Latin America and sub-Saharan Africa for large-scale projects, though environmental concerns and the availability of financing remain challenging.

Other renewable technologies are not on track to reach their 2DS targets. For CSP, the growth is seen mostly coming from emerging economies, especially South Africa, China and Morocco, where the largest plants with longer storage hours are expected to come on line. However, investment costs remain high, and further deployment needs a better remuneration of storage capacity. For bioenergy, despite a more optimistic outlook in Asia, with increasing co-firing and waste generation, most generation costs remain higher than conventional alternatives. For geothermal, pre-development risks remain high overall, and drilling costs have been increasing over the last decade. Ocean technology holds a great potential but requires faster cost reductions.

Recommended actions

In 2016, prospects for renewable electricity were more optimistic over the medium term, driven by policy improvements in key markets, cost reductions mainly for wind and solar technologies, and efforts to improve air quality. However, renewables are still at risk of falling short of longer-term 2DS power generation targets, with only solar PV and onshore wind being on track.

Accelerated growth of renewable electricity generation requires policy improvements focusing on three main challenges to deployment. First, policy makers should implement stable, predictable and sustainable policy frameworks, giving greater revenue certainty to renewables, and reducing policy uncertainties. Second, policies should address infrastructure challenges and market design issues to improve grid integration of renewables. Third, countries should develop policy mechanisms that reduce the cost of financing and lower off-taker risks, especially in developing countries and emerging economies.

In addition, some policies could also address technology-specific challenges. These policies could include: better remuneration of the market value of storage for CSP and pumped-storage technologies, ensuring timely grid connection and continued implementation of policies that spur competition to achieve further cost reductions for offshore wind, improved policies tackling pre-development risks for geothermal energy, and facilitating larger demonstration projects for ocean technologies. Other needed actions would involve developing the means to reflect the wider complementary policy drivers for sustainable bioenergy such as rural development, waste management and dispatchability, especially in competitive renewable energy auction framework.

4 Tracking by technology and region

Nuclear power

● Improvement needed
~ Limited developments

In 2016, nuclear power saw the highest capacity additions since 1990 (10 GW gross). New construction continued to fluctuate, with 3.2 GW commencing in 2016, down from 8.8 GW during the previous year, and averaging 8.5 GW over the past ten years. Capacity additions of 20 GW per year are needed to meet the 2DS targets.

Recent trends

Nuclear power accounts for approximately 11% of total electricity production and one-third of electricity from low-carbon sources. While the Paris Agreement is not technology specific, out of the 163 Intended Nationally Determined Contributions (INDCs) submitted by the end of 2016, only ten countries explicitly mentioned nuclear energy in their national strategies. These include countries with ambitious nuclear development programmes (China and India, for example). Premature closure of operational nuclear power plants (NPPs)[1] remains a major threat to meeting 2DS targets. A number of reactors in the United States are in jeopardy of shutting down in liberalised markets dominated by low natural gas prices, with nuclear largely excluded from financial incentives to other low-carbon generation technologies. In 2016, a considerable part of French nuclear capacity was offline owing to safety reviews.[2]

Projected nuclear growth remains strongest in Asia, as China released a new five year plan to more than double its 2015 capacity to 58 GW (net) by 2020, with an additional 30 GW (net) under construction at that time. However, with 31.4 GW (net) in operation at the end of 2016 and 21.5 GW (net) under construction, China will likely miss that target by a year or two. Korea also projects considerable growth – from 23 GW in 2016 to 38 GW by 2029. The Russian Federation (Russia) reduced its projections during 2016, noting that the reductions were to better align with reduced projections of electricity demand. In the United Kingdom, final approvals were given for the Hinkley Point C Contract for Difference after a government review of the entire project, and EDF Energy made the final investment decision in July 2016. Poland delayed a decision on its nuclear programme until mid-2017, citing the need to find a suitable financing model for the country, and Viet Nam abandoned plans to build two reactors due to lower electricity demand and the cost of nuclear technology compared with coal.

In terms of technology, the majority of reactors under construction today are Generation III/III+ designs. The first APR1400 and VVER1200 (Novovoronezh 2 in Russia) were connected to the grid in 2016. Efforts to develop and deploy small modular reactor (SMR) designs continued, with Argentina's CAREM reactor and Russia's and China's floating NPPs. In the United States, NuScale Power submitted the first-ever design certification application for an SMR to the US Nuclear Regulatory Commission. All of these SMRs are 100 megawatts electrical (MWe) or smaller.

Tracking progress

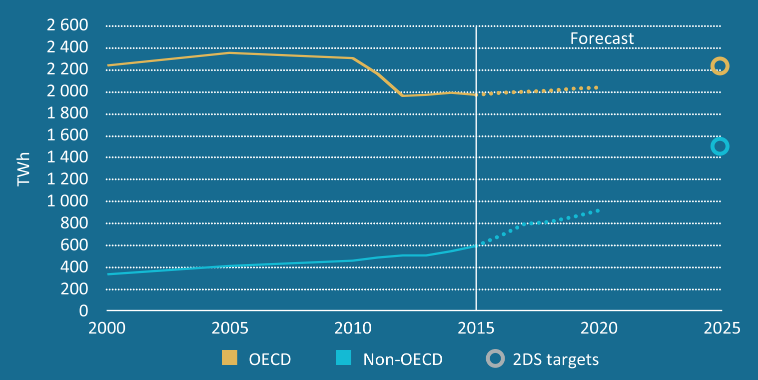
According to the most recent Red Book (NEA and IAEA, 2016), gross installed capacity is projected to be 402 GW to 535 GW by 2025; in the 2DS, global nuclear capacity would need to reach 529 GW by that time. Considering currently installed capacity of 413 GW and new capacity under construction of 66 GW, progress towards near-term targets has been positive. With another 20 GW of planned construction in the next three to four years, the remaining gap to the 2025 2DS target would be approximately 30 GW, which could be met if construction starts were sustained at the levels of 2009-10. However, retirements due to phase-out policies in some countries, long-term operation limitations in others or loss of competitiveness against other technologies could offset these gains. Up to 50 GW could be lost by 2025. Without action to address these reductions due to non-technical factors, the capacity will more likely be 70 GW to 90 GW short of the 2025 2DS target, unless annual grid connections double compared with the 2016 rate.[3]

Recommended actions

Increasing nuclear capacity deployment could help bridge the 2DS gap and fulfil the recognised potential of nuclear energy to contribute significantly to global decarbonisation. This requires clear and consistent policy support for existing and new capacity, including clean energy incentive schemes for development of nuclear alongside other clean forms of energy. In addition, efforts are needed to reduce the investment risk due to uncertainties, such as licensing and siting processes that have clear requirements and that do not require significant capital expenditure prior to receiving a final approval or decision. Industry must take all actions possible to reduce construction and financing costs in order to maintain economic competitiveness.

1-3. Refer to Technology overview notes on page 99.

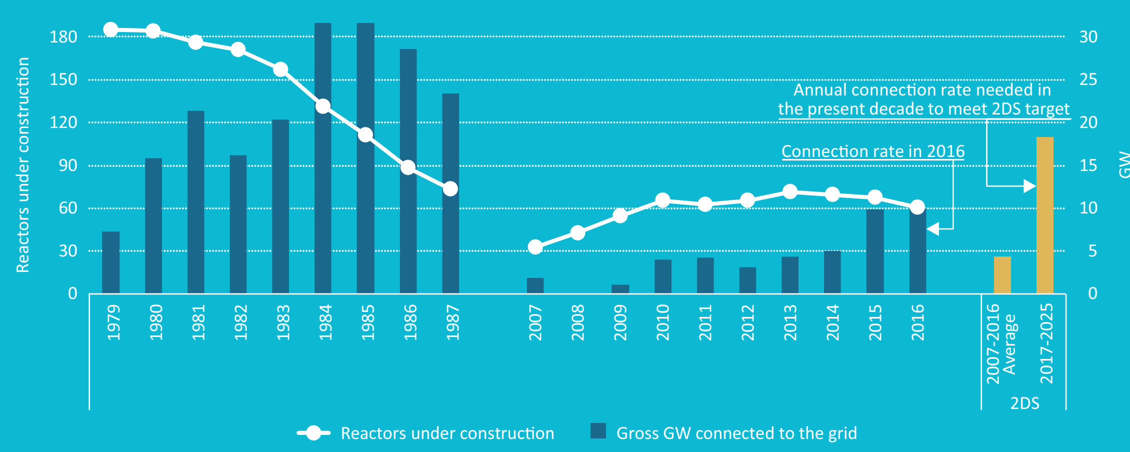
5 Nuclear electricity generation



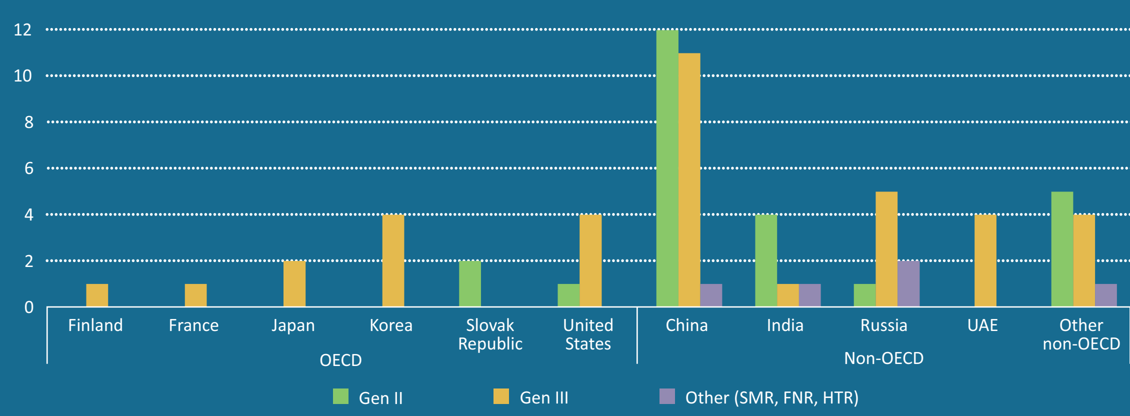
10GW

OF NUCLEAR CAPACITY ADDED IN 2016, THE HIGHEST ADDITION SINCE 1990

6 Capacity additions and reactors under construction



7 Reactors under construction



For sources and notes see page 99

Natural gas-fired power

● Improvement needed
~ Limited developments

Natural gas-fired power generation, which has an important role in the 2DS in helping reduce emissions by gradually displacing unabated coal-fired baseload generation, increased by 2.2% in 2014 (reaching 5 155 TWh). While this is generally in line with the 2.4% annual growth needed to achieve the 2025 2DS target, decline in 2013 and strong regional differences show the fragility of the growth path.

Recent trends

Gas-fired power generation in OECD countries recovered from the declines of the previous two years and increased by 7.1% in 2015 to 2 803 TWh. In the United States, 2015 gas-fired power generation reached a new record high (1 374 TWh) with coal-to-gas switching in the country also continuing to be strong in 2016. This trend is in contrast to gas generation in Europe, which remains well below its peak in 2008, despite strong growth in 2015 and 2016. Reductions in Japanese and Korean gas-fired power generation led a 5.7% decline in OECD Asia in 2015. Outside the OECD, gas generation in 2014 increased by 5.6% to 2 540 TWh and growth is estimated to have remained strong in 2015 and 2016. While demand grew in all major regions in 2014, the Middle East was responsible for around half of the increase.

Investments in gas-fired power declined by 40% in 2015 to USD 31 billion, leading to gas capacity additions of 46 GW. Combined-cycle plants accounted for roughly three-quarters of the additions in 2015. The Middle East, China and the United States were responsible for over half of the investment activity. Infrastructure considerations remain the main obstacle to stronger gas-fired power development in many developing countries, because the gas pipeline network needed to take advantage of low liquefied natural gas (LNG) prices often remains underdeveloped. As a result, coal remains the preferred fuel in many regions. In the United States, where gas prices are low and coal plants are being retired for economic and environmental reasons, investments have remained robust, although capacity additions were slightly lower than in previous years.

A major focus of gas turbine design is on flexibility performance, both for new-build plants and for retrofits of existing plants. Improvements in ramping capabilities, start-up times, turndown ratios and part-load behaviour are continuing in parallel with more moderate full-load efficiency improvements. Research on novel thermal coatings and cooling technologies continues to enable higher temperatures and efficiencies. State-of-the-art combined-cycle gas turbine (CCGT) efficiency now exceeds 60%, with expected improvements to 65% efficiency over the next decade. Top open-cycle gas turbine (OCGT) efficiency is at around 42%, up from around 35% in 1990.

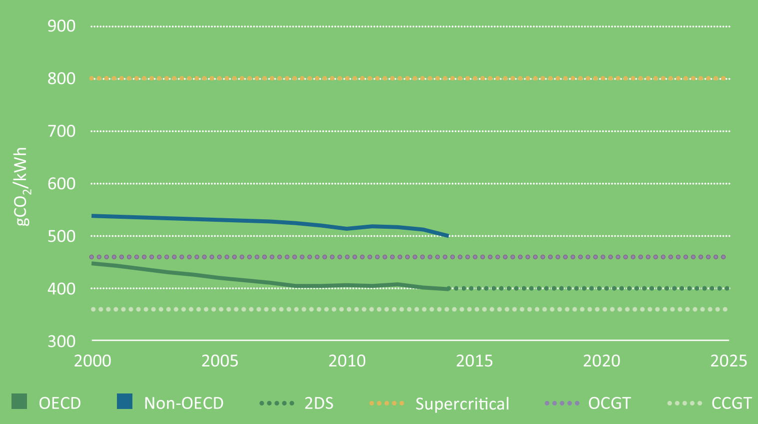
Tracking progress

The role of natural gas-fired power generation in the 2DS is twofold: first, to provide flexibility to support the integration of renewables, and second, as a lower-carbon alternative to coal-fired generation. Coal-to-gas switching will be of particular importance in the short term until 2025-30 in the 2DS, with strong deployment of both gas turbines and combined-cycle plants at the expense of coal. In the 2DS, gas-fired power generation increases over the next decade by roughly 2.4% per year. While this is markedly lower than the 2.2% observed in 2014 and the average over the last decade (3.9%), the volatility of the growth path over the last several years and pronounced regional differences indicate the fragility of gas generation growth. Additional progress in also needed in efficiency and flexibility performance of plants to provide support for the integration of variable renewables and serve as a short-term, lower-carbon alternative to coal plants, while preventing long-term stranding of gas plants. Gas is, however, increasingly competing not only with coal but also with other low-carbon alternatives that are already contributing to decarbonising the power sector in many regions, such as energy efficiency and renewable power generation.

Recommended actions

The competitiveness of natural gas relative to alternative generation technologies in the electricity system is highly dependent on regional market conditions. Carbon pricing, maximum emission caps and strict pollution regulations have proven their ability to establish competitiveness of gas with coal, and technology-neutral competitive mechanisms can ensure electricity supply security. With gas being a source of carbon emissions, R&D should increasingly also focus on gas power generation with CCS, because unabated gas, just like coal, is too carbon-intensive in the long run to reach the 2DS target.

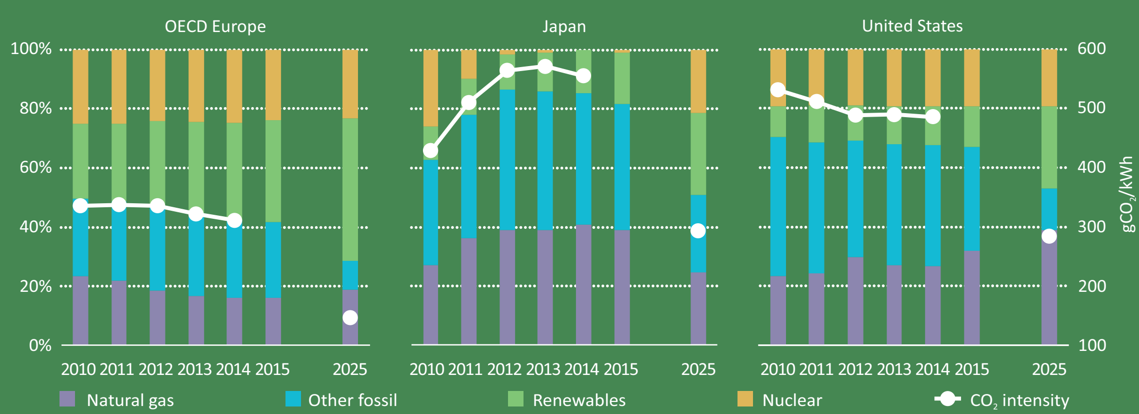
8 Natural gas-fired power technology intensity



2016

GAS FIRED POWER GENERATION EXCEEDS COAL GENERATION IN THE UNITED STATES FOR THE FIRST TIME

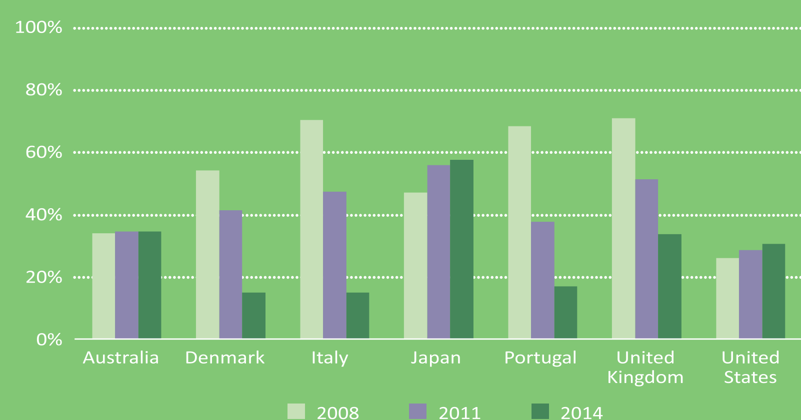
9 Power generation mix and related CO_2 intensity



31 USD BILLION

GAS FIRED POWER PLANT INVESTMENTS IN 2015

10 Natural gas-fired power capacity factors



Coal-fired power

● Not on track
~ Limited developments

Coal continues to dominate global power generation, with a share of over 40%. While generation growth has slowed, emissions from coal power would need to decline on average by 3% per annum until 2025 to be on track with the 2DS. In 2015, capacity additions stood at 84 GW, of which around 25 GW use subcritical technology. Under the 2DS, unabated coal capacity additions would have to slow down, with subcritical technology deployment abandoned altogether.

Recent trends

Coal's share in power generation remained at a notable level of 41% (9 690 TWh) in 2014, with generation growth of 0.7% from 2013 to 2014. Coal generation in 2015 and 2016 is estimated to have decreased, but pronounced regional and annual variations can be found. Coal-fired power generation in the major developed countries, in particular the United States, is on a steep downward trajectory while developing countries are still experiencing coal generation growth.

In OECD countries, power generation from coal decreased from 2014 to 2015 by 7.5% (−260 TWh) to an estimated 3 201 TWh, setting a new record low for the past decade. The main contributor to the decrease was the United States, which experienced a sharp decline of 14% (−239 TWh) compared with 2014, due to competitive gas-fired generation and the expansion of renewables. Electricity demand growth in OECD countries remains weak, and the share of coal in the overall generation mix fell from 32% to 30% in 2015.

Outside the OECD, coal generation in China, the centre of global coal demand, decreased in 2015 due to a reduction in electricity demand, coupled with an increased generation from hydro and nuclear.[1] Despite the decrease in generation in 2015, 52 GW of coal-fired generation capacity was added in China in 2015, and roughly 150 GW is currently under construction. In India, the third-largest coal consumer in the world, coal-fired power generation increased by 3.3% in 2015, which is considerably lower than the 11% growth of 2014, mostly due to lower demand growth.

Tracking progress

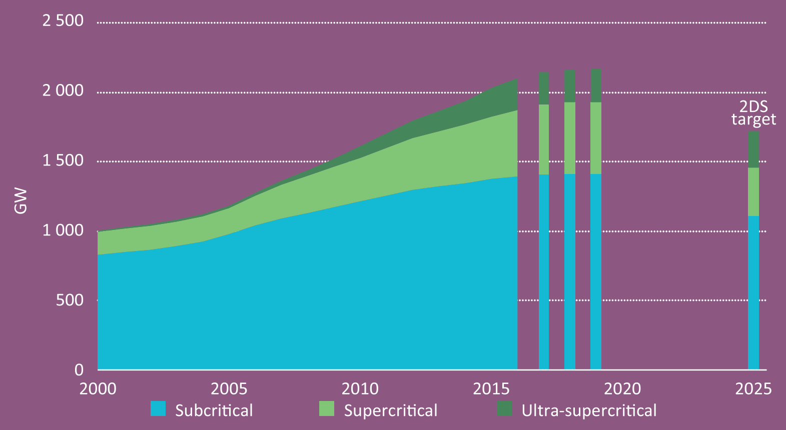
While coal generation growth has markedly slowed compared with the average of the past decade, and is estimated to have even contracted in 2015 and 2016, 84 GW of new coal capacity were still installed in 2015, almost 30% (25 GW) of which comprised subcritical technology, and around 280 GW are currently under construction worldwide, with roughly 10% being subcritical. According to 2DS projections, coal-based CO2 emissions must decline by around 3% annually by 2025. Further, to meet the 2DS targets, unabated coal generation needs to start to decline after 2020, led by a reduction in generation from the least efficient technologies.

Recommended actions

Policy measures need to address both the long-term and short-term challenges associated with generation from coal. Ultimately, a long-term carbon price signal will be needed to set adequate investment incentives and hence enable a low-carbon energy transition. For the short term, carbon pricing and more stringent pollution control regulations may be used to reduce emissions, minimise local air pollution, and limit and ultimately phase out generation from subcritical coal-fired power stations. Examples are emissions performance standards in Canada and the United Kingdom for power generation capacity additions as well as the carbon price support in the United Kingdom. In OECD countries, and especially in many emerging economies, where coal-fired power generation is set to expand in the near future, new-build coal-fired power units should aim for best available efficiencies (currently, through application of supercritical or ultra-supercritical technologies), where feasible, and be designed in view of potential future CCS retrofits, if they are not equipped initially with CCS. Further, coal plant designs should ensure sufficient operation flexibility to balance electricity supply and demand and to support the introduction of increasing shares of intermittent renewables onto the power grid.

1. Refer to Technology overview notes on page 99.

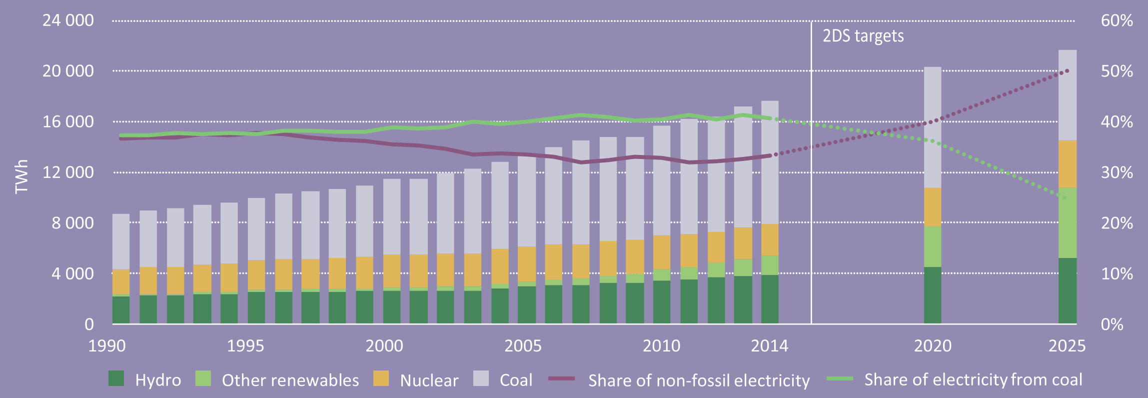
11 Coal capacity development



75%

OF INDIA'S ELECTRICITY IS GENERATED FROM COAL

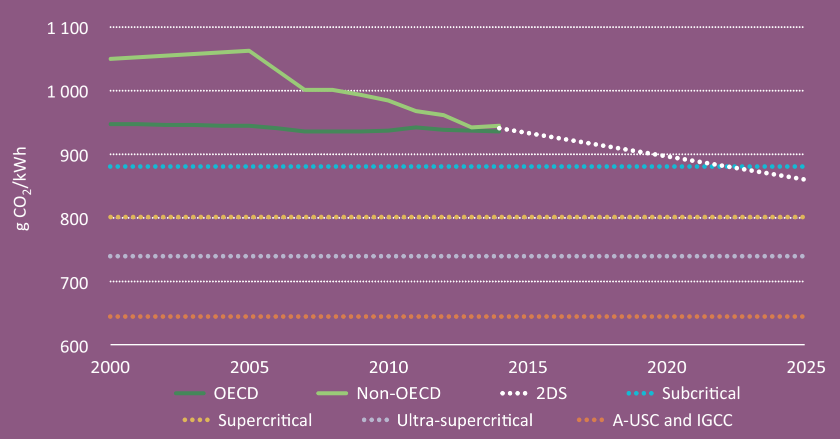
12 Coal and non-fossil power generation



84 GW

NEW COAL FIRED CAPACITY IN 2015

13 Emission factors from coal power generation



For sources and notes see page 99

Carbon capture and storage

● Not on track
↗ Positive developments

The global portfolio of large-scale CCS projects continues to expand. The first steel plant CCS project began operations in 2016 and the largest coal-fired CCS power plant started up in January 2017. Nevertheless, capture and storage capacity would need to expand tenfold to be on track to meet the 2DS in 2025. A renewed emphasis on CCS in long-term climate strategies and targeted support for project deployment are vital.

Recent trends

In 2016, the Sleipner CCS project in Norway marked 20 years of successful operation, having stored almost 17 $MtCO_2$ in a saline aquifer deep under the North Sea. The world's first large-scale CCS project in the iron and steel industry also commenced operation in 2016 in Abu Dhabi, capturing up to 800 000 tonnes of CO_2 annually.[1] At the beginning of 2017, the Texas Petra Nova project also came into operation as the largest post-combustion carbon capture system installed on an existing power plant, capturing up to 1.4 $MtCO_2$ annually.[2] The Illinois Industrial CCS Project is the world's first CCS project linked with bioenergy. The Tomakomai project in Japan also began CO_2 injection in April 2016. While not large-scale (it will capture 100 000 tonnes of CO_2 per year), the project will demonstrate the feasibility of CO_2 storage in formations under the seabed in Japan.[3]

Two further projects are expected to come on line in 2017, bringing the number of large-scale CCS projects operating globally to 19.[4] The Norwegian government announced it has included a grant of 360 million Norwegian kroner (NOK) (USD 45 million) in its 2017 budget for the continued planning of further full-scale demonstration facilities.[5] The Oil and Gas Climate Initiative (OGCI) has also announced its intention to invest up to USD 1 billion for CO_2 and methane reduction technologies and projects over the next ten years.

Tracking progress

CCS is not on a trajectory to meet the 2DS target of over 400 $MtCO_2$ being stored per year in 2025. The 17 operational large-scale projects have a total potential capture rate of over 30 $MtCO_2$ per year.[6] The capture and storage rate would need to increase tenfold in order to be on track to meet the 2DS in 2025. Furthermore, the 2DS annual target for CO_2 captured and stored from bioenergy projects leading to negative emissions is nearly 60 million tonnes (Mt) in 2025. A constant flow of projects through development to operation is crucial to meeting the targets under the 2DS and for maintaining and growing the global technical capacity in CCS.

While there is a surge in projects beginning operation over the 2016-17 timeframe, no CCS project took a positive investment decision or began advanced planning in 2016, causing concern that global progress will stall. Moreover, the number of projects under development has shrunk over the past years. Currently 10 projects are in development, with 5 under construction and 5 in advanced planning, down from a total of 18 in 2015.

Recommended actions

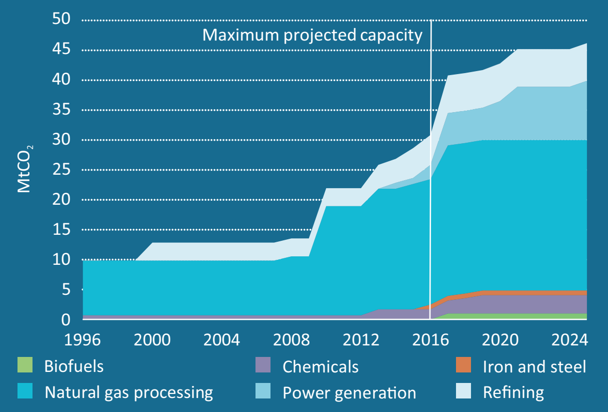
Governments should assess the value of CCS for their climate strategies. Early CCS deployment requires targeted financial and policy support to deliver deep emissions reductions. The current absence of adequate policy support is impeding progress with CCS, with implications for the achievement of long-term climate targets. Furthermore, an observed trend in decreasing CCS-related public RD&D investment over the last few years by IEA member countries should urgently be reversed.

Investment in geological CO_2 storage is an urgent priority, and government leadership is essential. Co-ordinated and extensive CO_2 storage assessment programmes are required to prove secure, practical and bankable CO_2 storage areas and sites in all key regions. Given the long lead times involved in developing CO_2 storage facilities, this effort must start now. Governments and industry should also ensure appropriate planning for and development of large-scale CO_2 transport and storage infrastructure, across jurisdictions where applicable.

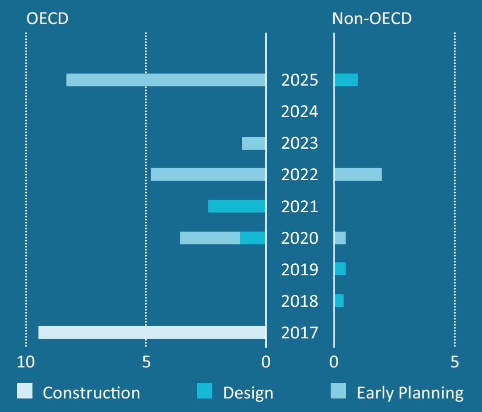
Creating the conditions for a separate CO_2 transport and storage business could address challenges experienced with integrated projects and underpin investment in CO_2 capture technology across power and industrial applications.

1-6. Refer to Technology overview notes on page 99.

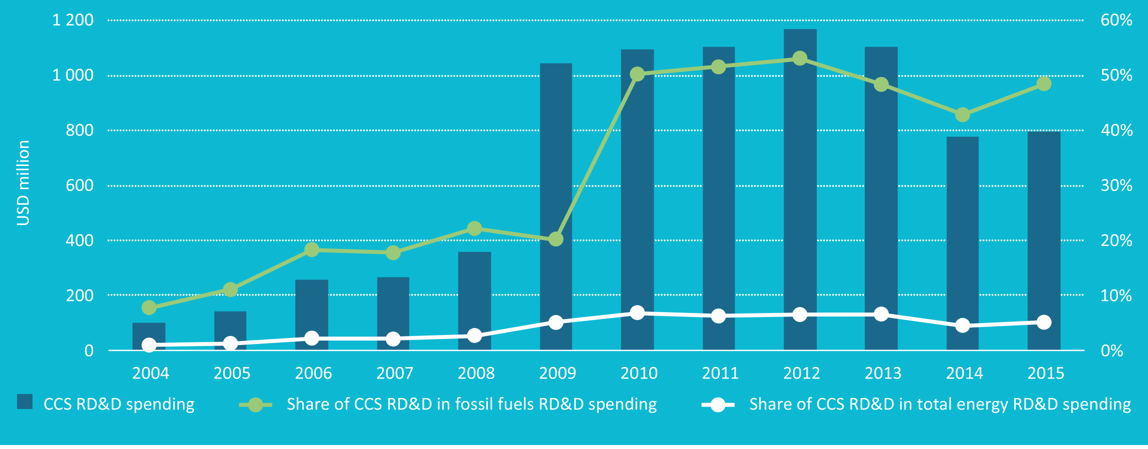
14 Large-scale CO_2 capture potential



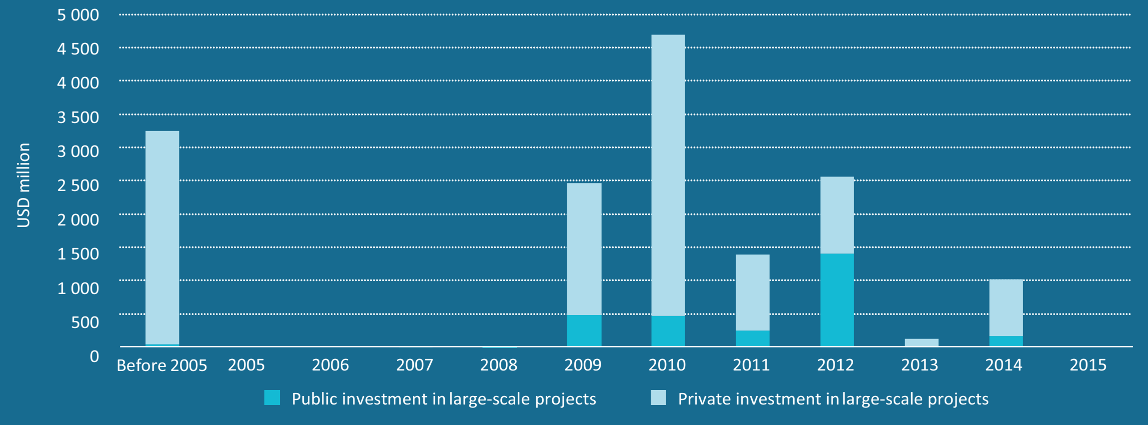
15 Capacity additions ($MtCO_2$)



16 IEA member public RD&D spending



17 Investments in large-scale CCS projects



For sources and notes see page 99

● Improvement needed
↗ Positive developments

Industry

The industrial sector[1] accounted for 154 exajoules (EJ),[2] or 36% of global total final energy consumption (TFEC) in 2014. The long-term trend of production growth in energy-intensive industrial sectors has continued, along with growth in the industrial sector's TFEC, which grew by 1.3% in 2014. Even as production continues to grow in the future, annual growth in energy consumption must be limited to 1.2%, to stay on a 2DS pathway, less than a half of the average 2.9% annual growth since 2000. Decoupling of industrial production from CO_2 emissions is also critical to meeting the 2DS pathway, which envisions 0.1% annual growth in CO_2 emissions by 2025 from 2014, compared with 1.1% in the RTS. In the 2DS, industrial CO_2 emissions need to peak by 2020.

Recent trends

Industrial sector energy consumption has grown by about 1.5% annually since 2010. Consumption of coal has grown fastest in recent years, more than doubling since 2000. Strong growth has also occurred in non-biomass renewables, such as solar thermal and geothermal, which have increased 80% since 2000 and have had the strongest growth of any fuel in 2014, at 7%. Structural effects based on changing shares of industrial subsectors, as well as regional shifts in production, could partly explain this, but the growth in renewable energy use in industry is nonetheless an encouraging sign.

The highest growth rate of industrial energy use occurred outside the OECD; the energy use of non-OECD countries grew 1.9% in 2014 compared with 0.2% for OECD countries, and continued to gain share of global industrial energy use, reaching 69% in 2014, up from 49% in 2000. Growth in energy use was strong in China (3.1%) and India (4.3%) in 2014.

Tracking progress

Energy-intensive industrial sectors have made progress in moving towards best practices and improving process energy efficiency. Industrial CO_2 emissions[3] have reached 8.3 $GtCO_2$ in 2014, 24% of global CO_2 emissions. ISO 50001, a certification for industrial energy management systems, continues to be deployed, reaching more than 12 000 sites in 2015, though 90% of those are located in North America and Europe, and deployment in other regions has been limited. Globally, post-consumer recycling has also been on an upward trend. Long capacity lifetimes and lack of co-ordinated international policies for industrial decarbonisation pose particular challenges in this sector, but energy-intensive industry has made some progress, which will need to accelerate to meet the 2DS. Annual growth in final energy consumption in industry must be limited to 1.2% from 2014 to 2025 to meet the 2DS, compared with 2.9% from 2000 to 2014.

Chemicals and petrochemicals

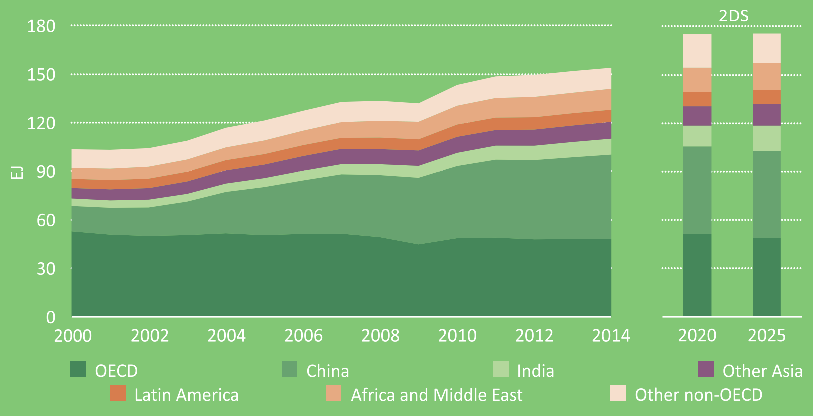
The chemicals and petrochemicals sector's share of global final energy consumption has grown from roughly 6% to 10% over the last four decades, and an increasing proportion of that energy input is used as feedstock, signifying this sector's growing prominence and an increase in process energy efficiency. Price trends in North American natural gas have contributed to a shift towards lighter feedstocks. Longer-term decarbonisation post-2025 requires additional effort on continuing to move towards less carbon-intensive production processes, improving process energy intensity, improving recycling of final products and continuing research on innovative, particularly bio-based, process routes.

Iron and steel

In 2014, 30% of global crude steel production was produced in electric arc furnaces (EAFs), growing from 29% in 2010,[4] and aggregated global energy intensity of crude steel production grew slightly to 21.3 gigajoules per tonne (GJ/t) from 20.7 GJ/t in 2011. Scrap availability puts an upper limit on the EAF share, though additional material efficiency and recycling will be important strategies for meeting the 2DS. New process routes, such as innovative direct reduced iron and smelting reduction technologies, which facilitate CCS, play important roles later in the 2DS.

1-7 Refer to Technology overview notes on page 100.

18 Total final industrial energy consumption by region

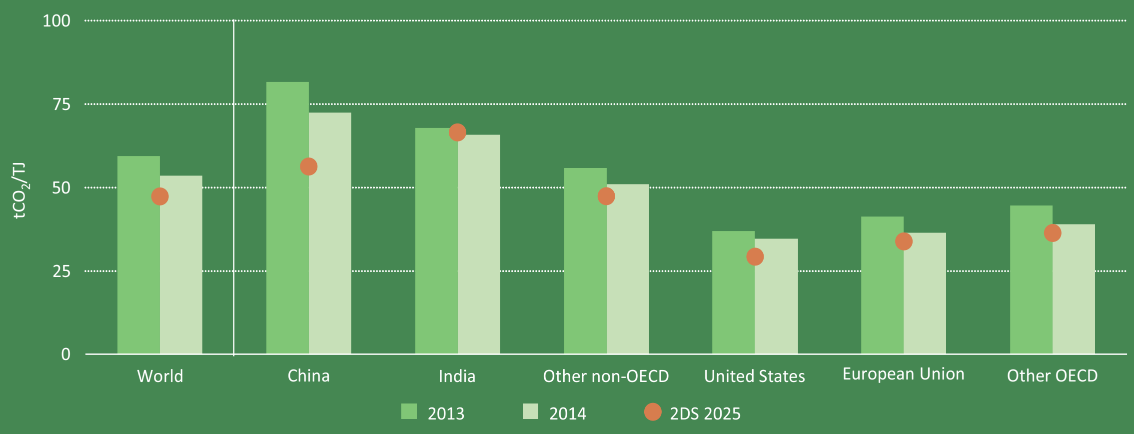


IN 2014,

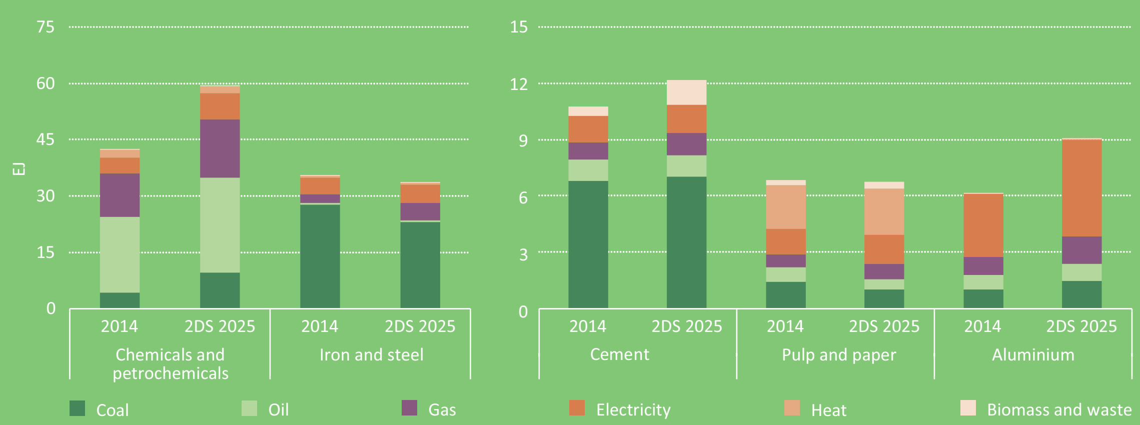
69%

OF INDUSTRIAL ENERGY USE WAS IN FIVE ENERGY-INTENSIVE SECTORS

19 CO_2 intensity of industrial energy consumption by region



20 Energy consumption by sector and fuel



For sources and notes see page 100

Short-term emissions reductions come mainly from energy-intensity improvements (47% of cumulative CO_2 reductions in the sector by 2025) and greater shifts to scrap-based EAF production (26% of CO_2 reductions by 2025).

Cement

Thermal energy intensity of cement kilns continues to improve, as higher-efficiency dry kilns replace older ones. Clinker ratio was about 0.65[5] on average in 2014 although in some regions significant potential exists to improve this ratio further to decrease the sector's CO_2 emissions, using new and existing clinker substitutes. Globally, biomass makes up about 2.0% of thermal energy consumption, and waste makes up an additional 3.3%; together they are envisioned to reach 12.4% by 2025 in the 2DS. The share of fossil fuels globally continues to decline. Process CO_2 emissions from the calcination of limestone remain an important challenge for the cement sector, and continued R&D for alternative products and processes, including CCS and new low-carbon cements, remains critical to the sector's pathway to 2DS.

Aluminium

The downward trend in energy intensity of both primary aluminium smelting and alumina refining continued, with the world averages decreasing by 1.9% for aluminium smelting and by 5.3% for alumina refining from 2013.[6] In 2014, 31% of aluminium was produced from scrap, maintaining nearly the same share as in 2013, despite 6.7% growth in overall production.[7] Meeting the 2DS pathways will require continued efforts to improve collection and recycling of scrap and SEC of both primary and secondary aluminium, along with R&D focused on alternative production routes, particularly those that address the process CO_2 emissions from primary smelting, such as inert anodes. Further, because this is an electricity-intensive sector, options to enable low-carbon grids, including demand-side management and decarbonised electricity sources, should also be considered.

Pulp and paper

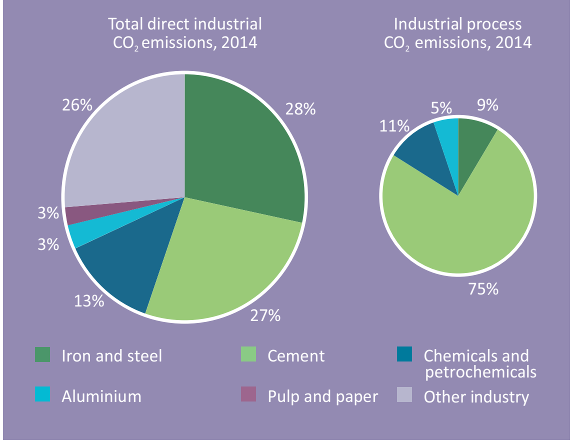
Production of paper and paperboard has been increasing, with demand growth in household and sanitary paper due to rising incomes counteracting the effects of digital technology displacing printing and writing paper. These structural effects have an impact, though growth in production has recently outpaced growth in energy consumption, suggesting a decoupling, and recovery and recycling of waste paper have also improved to 55.3% in 2014. The sector's energy use already includes a large share of biomass fuel and bio-based by-products. Energy intensity improvements, along with system-level thinking including utilisation of by-products, integration of pulp and paper mills, and integration of mills with grids or other sites with heat and electricity demand, will play a growing role in the 2DS. Growth in energy consumption must be limited to 0.1% per year to meet the 2DS, and CO_2 emissions must decrease 1.7% per year, compared with 0.2% and 0.9% growth, respectively, in the RTS.

Recommended actions

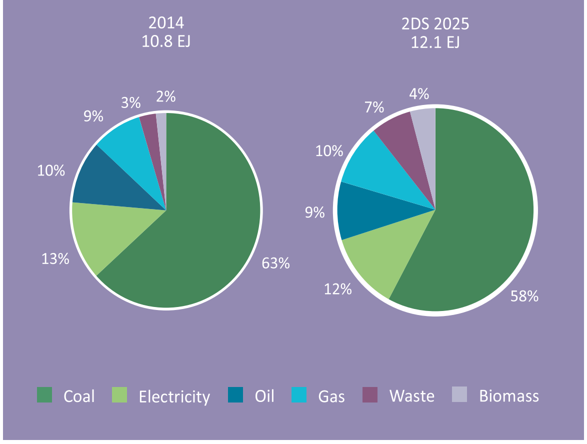
Throughout the industrial sector, pre-2025 emissions reductions rely on implementation of best available technology (BAT) and continued work towards energy efficiency. Increasing post-consumer scrap recycling rates and utilising this scrap to offset primary production of materials would significantly reduce the energy and emissions intensity of production, and thus should be promoted. All sectors should also consider possibilities for sustainable utilisation of industrial wastes and by-products as well as recovering excess energy flows. Implementation of these existing solutions, especially the low-cost, low-risk commercially available processes and technologies, will be a critical driver of the early phase of the 2DS transition. Policy makers should put in place a policy framework that incentivises decarbonisation while considering the impacts in terms of carbon leakage and competitiveness.

In the longer term, deeper cuts in industrial CO_2 emissions will require innovative new low-carbon process routes and products. To ensure the future availability of those processes and technologies, the sector should focus R&D in the near term on low-carbon production and mitigation options. Furthermore, deployment of innovative technologies is needed at both pilot and commercial scale. This deployment will require collaboration across companies, sectors and national borders. Existing efforts should be accelerated, and policy frameworks put in place to incentivise low-carbon innovation.

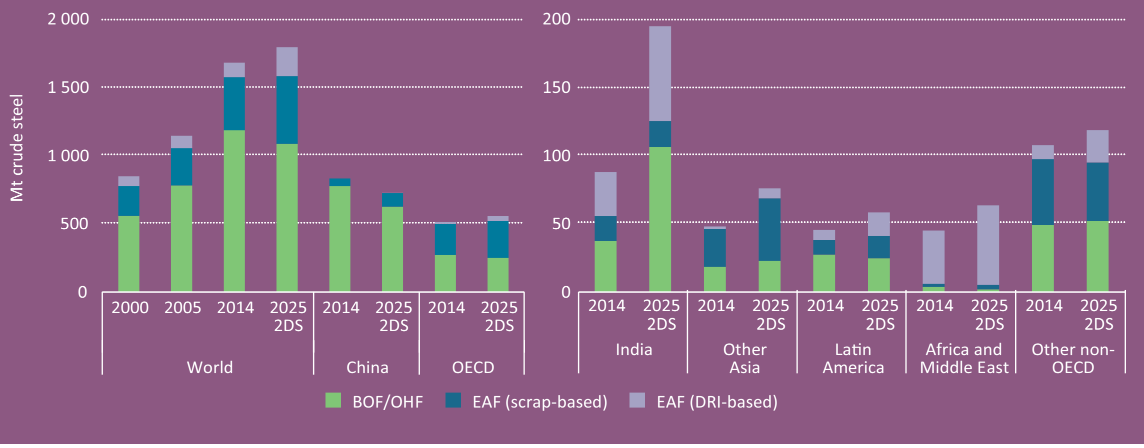
21 Direct industrial CO_2 emissions



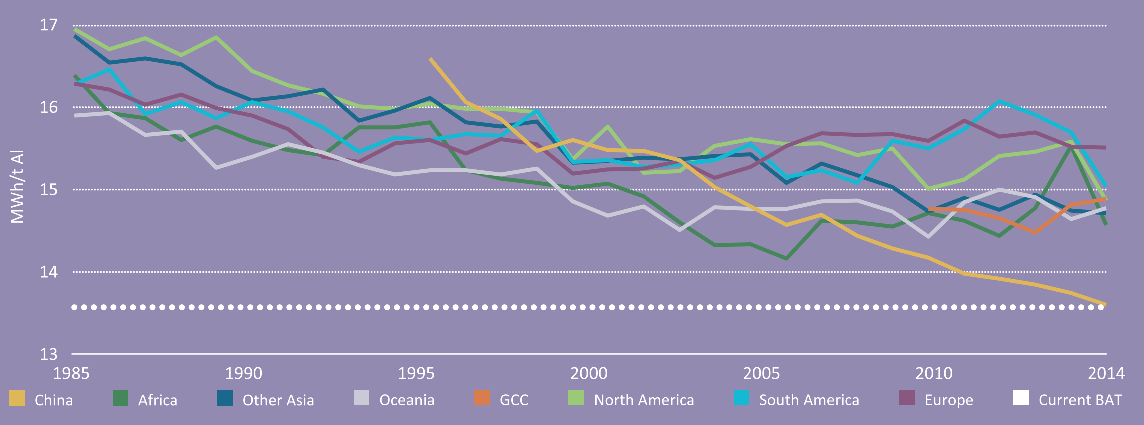
22 Cement production energy use



23 Crude steel production by process route



24 Primary aluminium smelting electricity intensity



For sources and notes see page 100

Chemicals and petrochemicals

● Improvement needed
↗ Positive developments

The chemicals and petrochemicals sector remains the largest industrial energy user, accounting for 28% of industrial final energy consumption in 2014. Of the sector's total energy input, 58% was consumed as feedstock. To remain on a 2DS trajectory, annual increases in process energy consumption must stay below 3.6% and direct CO_2 emissions below 3.6% during 2014–25, a period in which demand for primary chemicals[1] is projected to increase by 47%.

Recent trends

Global production of high-value chemicals (HVCs),[2] ammonia and methanol recovered the ground lost during the global financial crisis, growing by 19% (HVCs), 13% (ammonia) and 51% (methanol) over the period 2009–14.

Major shifts in the fossil fuel landscape in recent years have had significant impacts on the global feedstock mix. Notably, the shale boom in the United States has contributed to a regional divergence in natural gas prices, resulting in a cost advantage for US chemical producers reliant on lighter feedstocks[3] such as ethane and liquefied petroleum gas (LPG). A 16% increase in global ethane steam cracker capacity between 2010 and 2014 accompanied this shift.

The production of HVCs, ammonia and methanol accounted for 73% of the chemicals and petrochemicals sector's total energy use in 2014. Actual SEC[4] values for these large volume processes are 12.5 GJ/t HVC to 34.6 GJ/t HVC of process energy for HVCs, 10.4 GJ/t to 31.4 GJ/t for ammonia, and 11.6 GJ/t to 25.1 GJ/t for methanol.[5]

Bio-based routes to both primary chemicals and downstream chemical products present promising avenues for decarbonisation. Bio-routes to primary chemicals, such as bioethanol-to-ethylene and biomass-based ammonia and methanol, exist mainly at pilot scale. Global production capacity of bioplastics totalled 1.7 Mt in 2014, but was dwarfed by the overall plastic materials demand of 311 Mt.

Tracking progress

Average annual growth in the sector's process energy consumption[6] and direct energy-related CO_2 emissions was 2.3% and 2.6%, respectively, during 2000–14. Energy use as petrochemical feedstock, which grew 2.3% annually during the same period, also plays an important role, with over half of the sector's energy consumption and 19% of its direct CO_2 emissions. Annual average increases in process energy consumption and direct energy-related CO_2 emissions through 2025 must stay below 3.6% and 2.8%, respectively to meet the 2DS trajectory. Future evolution of energy prices, feedstock-related CO_2 emissions, and demand for chemical products could be challenges to a long term transition to low CO_2 production.

Process energy use for the production of HVCs, ammonia and methanol accounted for 32% of sector's TFEC in 2014, increasing slightly to 33% in 2025 in the 2DS. Global average declines in the process energy intensities of the sector's main products – 13% for HVCs, 5% for ammonia and 15% for methanol – are outpaced by the energy savings from shifts to higher yielding feedstocks.

Two levers provide the majority of the 2DS' direct CO_2 emissions savings in 2025, relative to the RTS: process energy efficiency (78%) and switching to lighter fuels and feedstocks (18%). The remaining 5% is provided by increased plastics recycling. Post-consumer waste plastic collection rates, recycling yield rates and the extent to which recycled polymers displace virgin resin consumption (i.e. reduced down-cycling) all increase steadily until 2025. These increases deliver 9.8 Mt of annual primary chemical savings in the 2DS in 2025, compared with the RTS.

Recommended actions

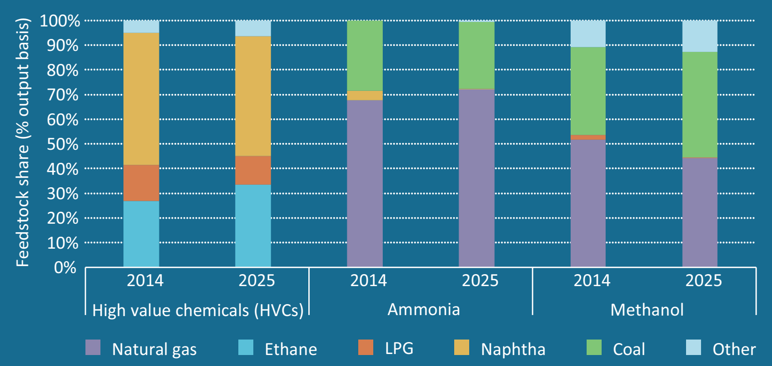
Two key categories of sector-specific mitigation options should be given priority in the short to medium term. The first category is fostering best practices among existing plant operators to lower energy and emissions intensities for key production processes. The second category is removing barriers to enhancing resource-efficient production and waste treatment. Ensuring the presence of price signals to incentivise resource efficiency strategies throughout the chemicals value chain can promote positive action. Harm to competitiveness can be minimised if collective action is taken globally.

Both the quality and quantity of publicly available statistics in the chemicals and petrochemicals sector have long needed to be improved. The appraisal of policy initiatives, such as those noted above, requires detailed and robust statistics.

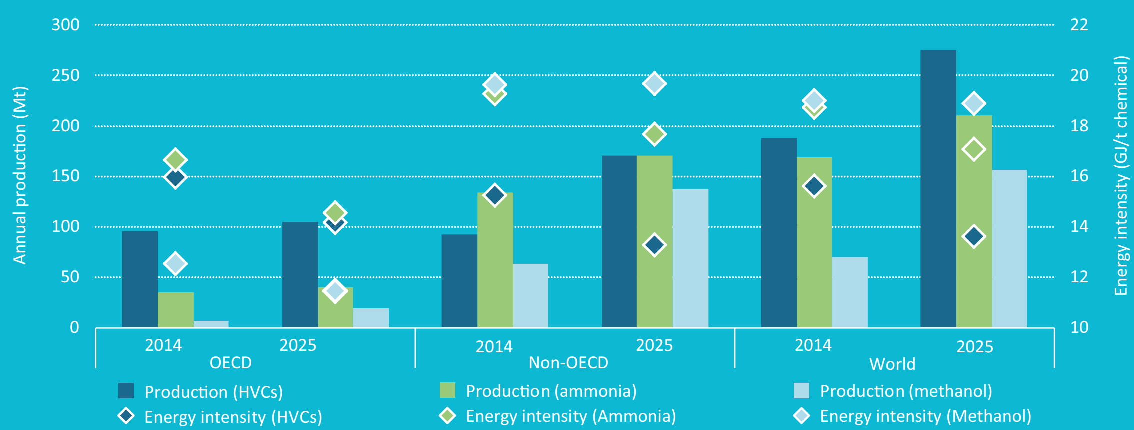
1-6. Refer to Technology overview notes on page 100.

THE (PETRO) CHEMICALS SECTOR ACCOUNTED FOR **28%** OF INDUSTRIAL ENERGY CONSUMPTION IN 2014

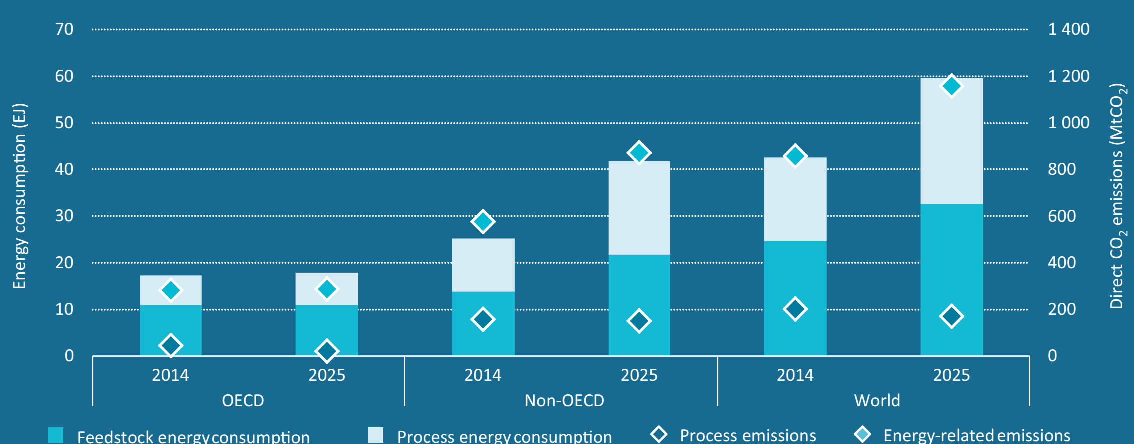
25 Feedstock shares for primary chemicals



26 Production and energy intensity for primary chemicals



27 Sector-wide energy consumption and CO_2 emissions



For sources and notes see page 100

Pulp and paper

● Improvement needed
↗ Positive developments

The pulp, paper and printing sector[1] accounted for 5.6% of industrial energy consumption in 2014. Though its share of industrial energy use has been in decline since 2000, the sector continues to be among the top industrial energy consumers, and can play an important role in the transition to a low-carbon energy system. Despite production growth, the sector's energy use must decline by 0.8% and direct non-biomass CO_2 emissions by 17% by 2025 from 2014 levels to meet the 2DS.

Recent trends

Annual production of paper and paperboard has increased by 23% since 2000 (FAO, 2016), with growth in demand for household and sanitary papers due to rising populations and incomes, and rising packaging material needs for shipping of consumer goods. These trends have offset reduced demand for printing and writing papers in an increasingly digital age. The share of wood pulp in paper production[2] has decreased over time, from 52% in 2000 to 43% in 2014 (FAO, 2016), as rates of waste paper recovery and recycling continue to improve.

Fossil fuels, which are primarily used for onsite utilities, accounted for 42% of total energy consumption in 2014. Decarbonising these utilities by switching to lower-carbon fuels could have an important impact.

Pulp and paper production has a high share of biomass in its energy consumption, due to the use of by-products. For each tonne of kraft process pulp,[3] an estimated 19 gigajoules (GJ) of black liquor[4] is produced, which can be used for steam and electricity generation. Sawdust, wood chips and other wood residues (called "hog fuel") are also generally burned on site. An estimated 0.7 GJ to 3.0 GJ of hog fuel is produced per tonne of wood pulp.

Tracking progress

The sector's energy use has grown only 1% since 2000, despite a 23% increase in paper and paperboard production, which points to a decoupling of growth in energy use and production. However, structural effects, such as shifts in product mix or regions of production, can also influence energy use, and data quality issues make it difficult to draw concrete conclusions about the energy intensity trends.

Recovery and recycling of waste paper have steadily been increasing. The utilisation of recovered paper in the total fibre furnish grew to 55.3% in 2014, up from 44.3% in 2000 and 33.9% in 1990. This trend is envisioned to continue, growing to 57.6% in the 2DS by 2025.

Research on innovative processes for pulp and paper manufacturing has continued to identify opportunities for decarbonisation. The Confederation of European Paper Industries (CEPI), for example, led an initiative called the Two Team Project, which brought together researchers to identify the most promising breakthrough technologies for decarbonisation, in an example of collaborative and open R&D. New concepts identified through this project will require additional research and funding to bring to scale.

Tracking of energy efficiency improvements in pulp and paper manufacturing is difficult, because publicly available data on production, capacity and energy use are limited. Additionally, some countries do not report biomass use for the pulp and paper sector, which makes it difficult to get an accurate picture of the sector's energy needs.

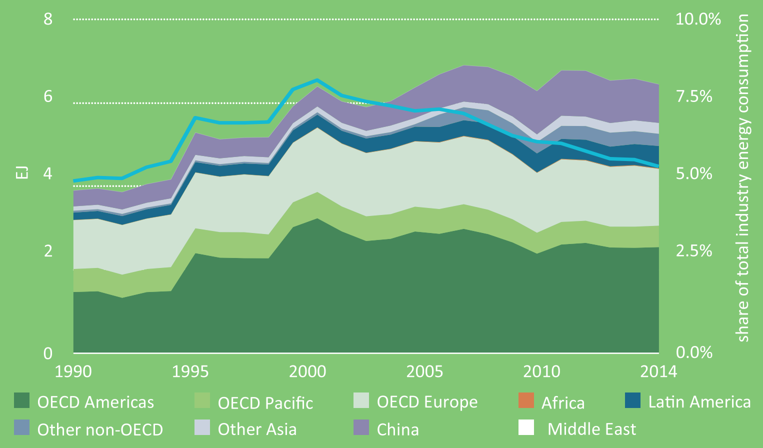
Recommended actions

Through 2025, the sector should continue to focus on improving energy efficiency, moving towards BAT-level performance and increased recycling, while also supporting R&D efforts to develop future processes and technologies.

In the longer term, the sector can also contribute to sustainable energy supply, for example, by feeding excess heat and electricity into the grid. The concept of pulp mills as integrated bio-refineries that produce low-carbon energy commodities, including biofuels for transport, from black liquor alongside their pulping activities is gaining traction, and several pilot projects are under way. The sector also has the opportunity to contribute some negative emissions by capturing biogenic CO_2 emissions. Similarly, new applications for pulp and paper products may contribute to product life-cycle CO_2 emissions reductions, for example, through improved packaging or fibre-based textiles. Private- and public-sector stakeholders should collaborate to ensure the necessary framework of incentives is put in place to encourage such strategic and systemic thinking.

1-4. Refer to Technology overview notes on page 101.

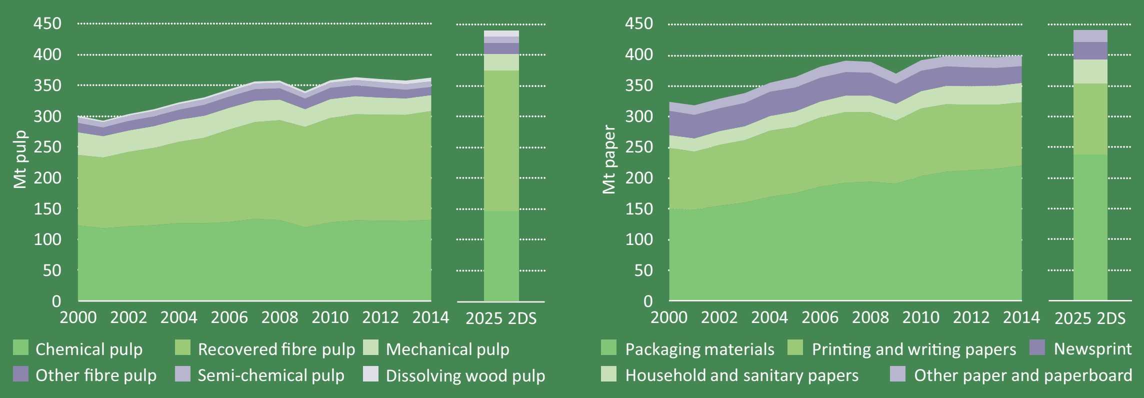
28 Final energy use by pulp, paper, printing



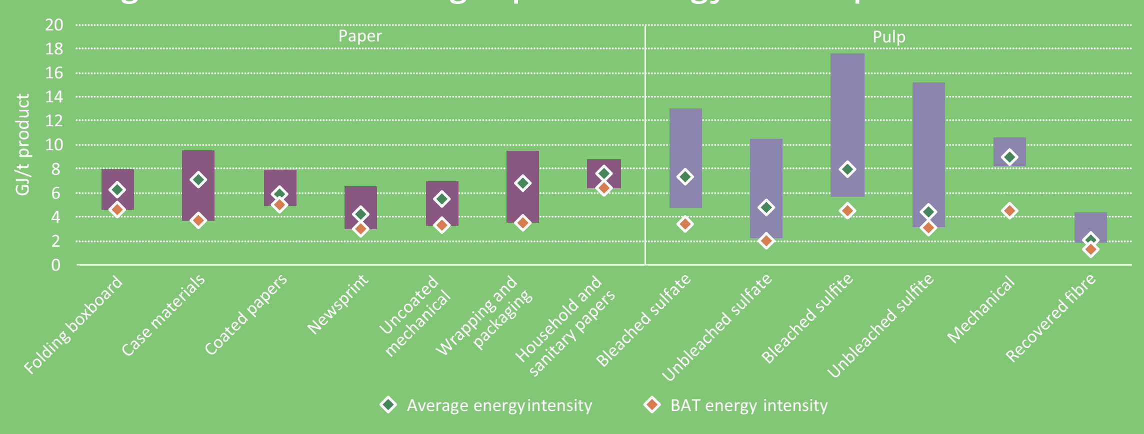
55%

OF FIBRE USED FOR PULP MANUFACTURING GLOBALLY IN 2014 WAS FROM RECOVERED WASTE PAPER, UP FROM 44% IN 2000

29 Production of pulp, paper and paperboard



30 Ranges of national average specific energy consumption



For sources and notes see page 101

Transport

● Improvement needed
~ Limited developments

Transport's share of global energy-related CO_2 emissions is 23%. Emissions increased by 2.5% annually between 2010 and 2015. This trend must be reversed to get on track with 2DS targets. NDCs to the Paris Agreement targeting transport are insufficient to bring sectoral emissions in line with the 2DS.

Recent trends

With the submission of NDCs to the Paris Agreement, a long-term political signal was sent to decarbonise the transport sector. More than three-quarters of NDCs explicitly identify transport as a mitigation priority; around two-thirds propose sectoral mitigation measures; and 9% specify a transport sector emissions reduction target (PPMC, 2016). A strong bias towards passenger transport is evident in the NDCs. Developing regions tend to highlight a commitment to urban public transit such as bus rapid transit systems (PPMC, 2016). Fuel economy standards and e-mobility pledges are also prioritised to varying degrees, especially in developed economies.[1] Freight is mentioned in only 29% of NDCs, and the most widely cited measure is to target a shift from road to rail and/or ships (PPMC, 2016).[2]

In 2016, a global market-based measure was introduced to mitigate CO_2 emissions from international aviation (ICAO, 2016). The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) aims to stabilise CO_2 emissions from international aviation by 2020. Emissions exceeding the threshold would be offset (ICAO, 2016).[3] The IMO also agreed on a global sulphur cap of 0.5% on marine fuels (IMO, 2016),[4] but has not yet defined a GHG emissions mitigation target.

Tracking progress

Global transport sector GHG emissions continue to grow. To reach 2DS targets, sectoral emissions must begin to decline within the coming decade. OECD economies must reduce "wheel to wheel" (WTW) GHG emissions by more than 20% by 2025 to offset continued emissions growth of more than 18% in non-OECD countries over the same period.[5,6] Transport-related mitigation measures proposed in NDCs are expected to fall short of both medium- and long-term 2DS targets.

Positive trends continue in electrification. Sales of EVs continue to increase, with the light-duty EV market growing by 50% (EVI, 2017) compared with 2015, with China leading market growth.

Aviation, shipping and heavy-duty road are the most difficult modes to decarbonise. Despite the aforementioned adoption of new regulatory policies and other measures, these sectors are still under-regulated when compared with LDVs. The WTW GHG emissions of the shipping sector, for example, are expected to grow at a rate of 1.9% per year from 2015 to 2025 in the RTS, and aviation at 2.0% per year. However, emissions must stabilise in these sectors to align with the 2DS by 2025, and decline rapidly afterwards. Road freight WTW GHG emissions grow by 2.2% per year over the same period in the RTS, but here emissions growth must be capped at 1.0% to meet the 2DS targets.

Recommended actions

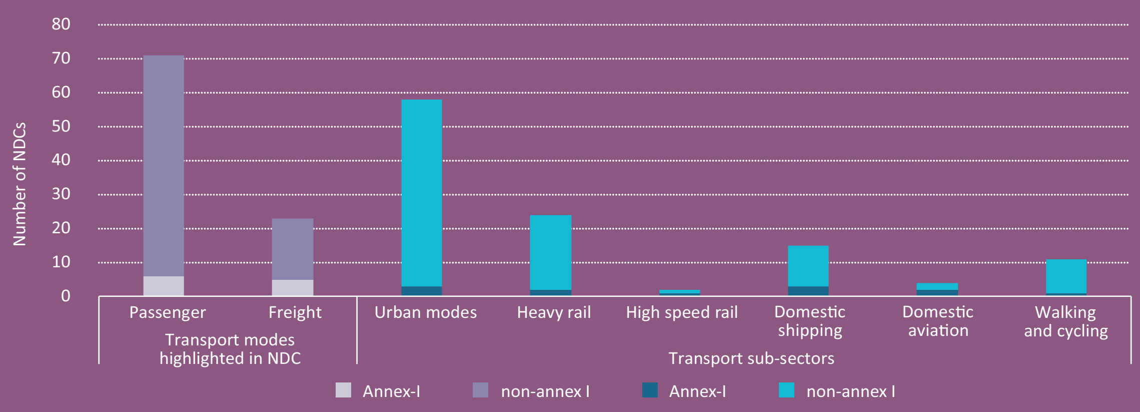
The ambition expressed in the NDCs must translate into concrete actions to put transport on track with 2DS targets. Mode-specific measures should target proven and rapid means of reducing emissions.

Policies must raise the costs of owning and operating the modes with highest GHG emissions intensity to stimulate investments and purchases of energy-efficient and low-carbon technologies and modes. A price on carbon is essential, and could be particularly effective in reducing GHG emissions from shipping and aviation, sectors that are currently subject to low or no fuel taxation. Complementary additional measures are also needed, including investments in energy-efficient transport modes (such as rail and public transport), regulations mandating ambitious vehicle efficiency improvements[7] and measures encouraging the adoption and development of low-carbon fuels.

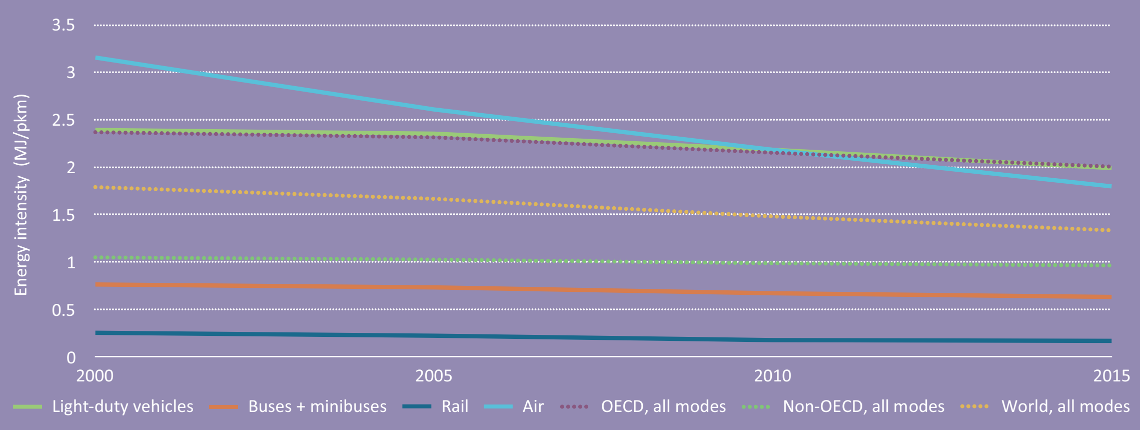
The development of CORSIA has both positive and negative implications. The acknowledgement of the need for climate change mitigation and the elaboration of a unified aspirational goal for the industry are both welcome developments. But these developments could come at the expense of reduced pressure for R&D solutions that could be achieved within the aviation industry itself. The international shipping sector should consider a similar unified mitigation goal. However, in light of the large potential to reduce specific CO_2 emissions,[8] the international shipping sector should adopt carbon taxes rather than offsets.

1-8. Refer to Technology overview notes on page 101.

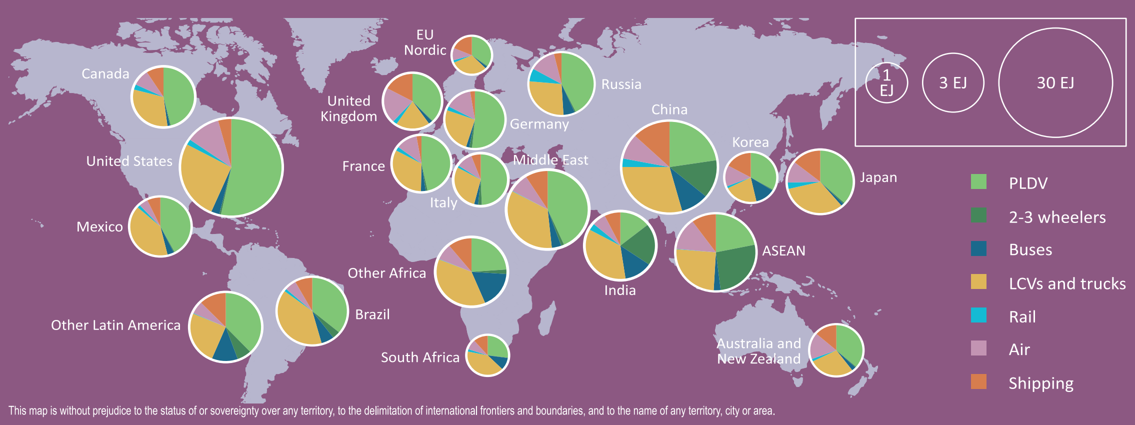
31 Share of mitigation measures by mode in NDCs



32 Energy intensity development – Passenger modes



33 Transport energy use, by mode, 2015



For sources and notes see page 101

Electric vehicles

● On track
~ Limited developments

With over 2 million electric cars[1] on the road and over 750 000 EVs sold worldwide in 2016, a new historic record has been achieved in the electrification of individual transportation. The 2016 sales show a slowdown in market growth rate compared with the previous year – 40% in 2016 versus 70% in 2015 – suggesting an increasing risk to diverge from a 2DS trajectory.

Recent trends

Globally, 753 000 plug-in EVs were sold in 2016, 60% of which were battery-electric cars (BEVs). These sales were the highest ever registered and allowed the global EV stock to hit the threshold of 2 million units in circulation. China remained the largest EV market for the second consecutive year and, in 2016, accounted for close to half of global EV sales. Europe represented the second-largest global EV market (215 000 EVs sold), followed by the United States (160 000 EVs sold). Plug-in hybrid electric cars (PHEVs) gained ground compared with BEVs both in Europe and in the United States. Norway, with a 29% market share,[2] and the Netherlands, with 6%, have the highest EV market penetrations globally. Sizeable drops in EV sales and market share took place in the Netherlands and Denmark, primarily reflecting changes in policy support. Overall, EVs are still a minor fraction (0.2%) of all cars in circulation.

Despite the slowdown in growth rates, the increase in EV production continues to favour technology learning and economies of scale. Battery costs kept declining between 2015 and 2016, and energy density continued to increase (EVI, 2017). This, combined with the improvements expected from battery chemistries that are currently being researched, gives encouraging signs on the possibility to meet the targets set by carmakers and the US DoE for the early 2020s (EVI, 2017). Battery technology improvements will enable longer ranges to be achieved at lower costs, increasing the cost-competitiveness of EVs and lowering barriers to adoption.

Publicly accessible charging infrastructure attained 320 000 chargers globally. Fast chargers, which use high-power alternating current, direct current or induction, and can fully recharge a BEV in less than an hour, are mostly located in China and make up a third of all chargers operating globally. In 2016, on a global average and with the exception of China, the deployment of fast chargers was slower than the deployment of chargers overall. This trend may reflect difficulties in their economic viability.

1-2. Refer to Technology overview notes on page 102.

Tracking progress

EV sales growth remained strong, with a 40% increase in 2016 over the previous year, but declined significantly from the 70% growth of 2015. The 2016 sales still allow for the 2DS sales and stock objectives to be attained by 2025 under the condition that the 2016 growth rate is maintained in future years: meeting the 2025 target implies an annual sales growth of 35% every year from 2017 to 2025. Thus recent manufacturers' announcements regarding ambitious EV production plans must be followed by concrete investment decisions.

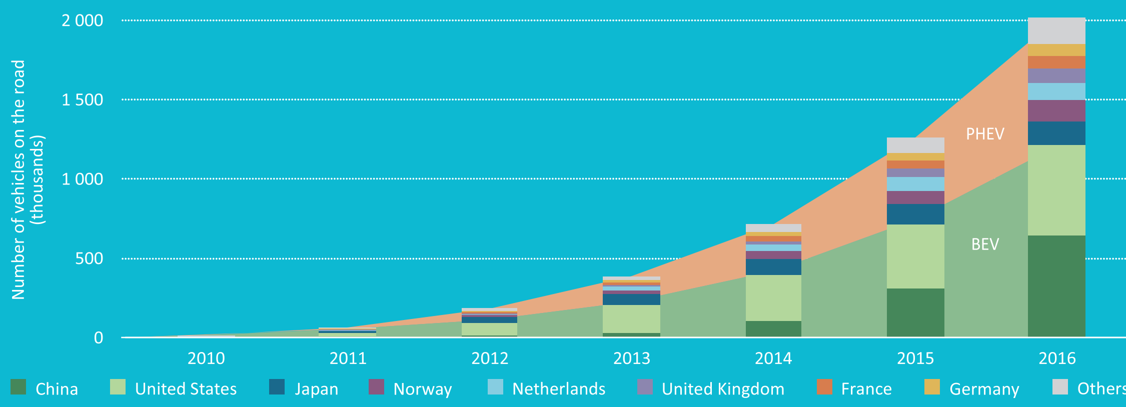
Recommended actions

Financial incentives, EV performance and the availability of charging infrastructure emerged as factors positively correlated with the growth of EV sales. Public policies aiming to reduce the purchase cost gap between EVs and conventional cars and to improve the value proposition of EVs, including, for instance, public procurement programmes and awareness campaigns, are, therefore, well suited to stimulate EV adoption. Furthermore, a supportive policy environment also reduces risks for investors.

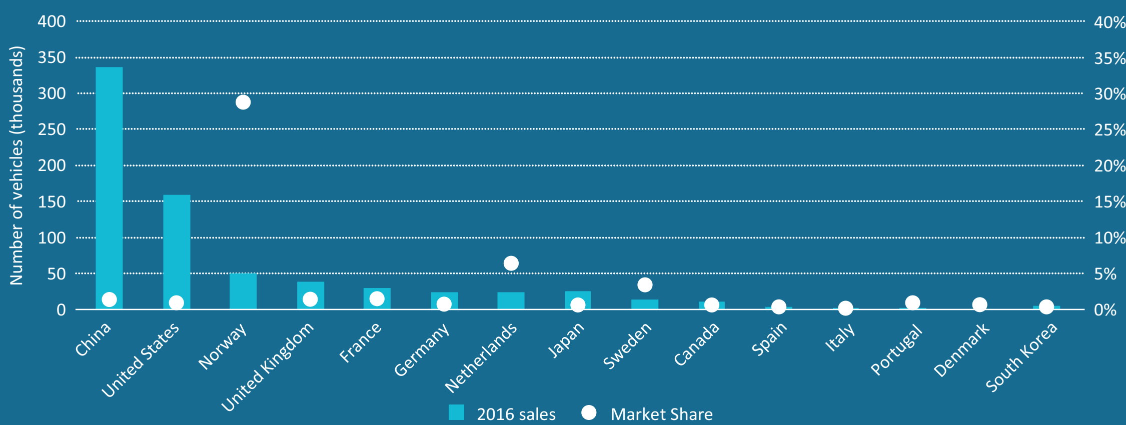
Policy support needs to be comprehensive by taking place at different administrative levels, from national to local, under different forms: direct support for research, vehicle purchase subsidies, zero-emission mandates, fiscal advantages for charger deployment, tightened fuel economy standards, and differentiated taxes, fees and restrictions on the basis of vehicle emissions performance, such as regulations on access to urban centres (e.g. zero-emission zones). The cost-attractiveness of EVs can also be enhanced as conventional fuels become more expensive, via fuel taxes that include carbon pricing, which needs to be implemented in parallel with grid decarbonisation efforts.

As EVs become more popular, securing affordable raw material supplies will become increasingly critical to ensure that improvements achieved in battery costs can be sustained. This task can be simplified through the early development of regulatory requirements for second life of batteries and material recycling.

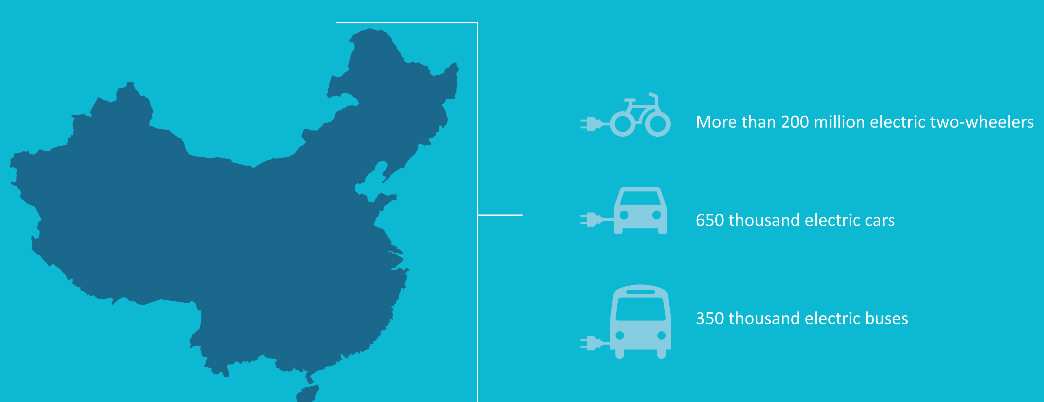
34 Evolution of the electric car stock (BEV and PHEV), 2010-16



35 EV sales and market share in a selection of countries, 2016



36 Focus on China



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.

For sources and notes see page 102

International shipping

● Not on track
~ Limited developments

The shipping sector is a key enabler of international trade and constitutes the most energy-efficient way to move goods. But limited policy deployments have led to a slow uptake of clean technologies in shipping. Meeting 2DS goals requires the rapid adoption of markedly more ambitious policies.

Recent trends

The shipping sector accounts for 80% of global trade in physical units and 2.0% of CO_2 emissions from fuel combustion. Shipping activity is closely linked to gross domestic product (GDP) growth.[1] Both shipping activity and GDP have increased steadily, by 3.8% and 3.6% per year from 2000 to 2015, respectively (UNCTAD, 2016; World Bank, 2017). International shipping energy demand increased by 1.6% per year from 2000 to 2014.[2] Historically, shipping energy use has also been closely correlated with GDP growth; however, a decoupling of this trend has been observed since around 2010 (IMO, 2014). This matches a decline in trade activity in 2009 and a slow subsequent recovery after that, as well as a trend towards upgrading of the global container fleet to larger and more efficient ships beginning in 2011.[3] The vast overcapacity resulting from this led to the early retirement of old and inefficient ships, and boosted the energy efficiency per tonne kilometre (tkm) of the global fleet by an unprecedented average annual rate of 5.8% from 2010 to 2014. Slow steaming, which has become more common in response to overcapacity, also led to operational efficiency improvements (IMO, 2014; ITF, 2017).

In 2013, the IMO introduced the EEDI, the first energy efficiency standard for new ships, mandating a minimum improvement in the energy efficiency per tonne kilometre of new ship.[4] A global sulphur cap of 0.5% on marine fuels will also come into force in 2020 (IMO, 2016). Meeting this cap will require significant changes in the fuel mix and may lead to higher maritime fuel prices. Heavy fuel oil (HFO) (currently 84% of the marine bunkers fuel mix)[5] will also have to be desulphurised or replaced by low-sulphur diesel, LNG, biofuels or other synthetic fuels. Alternatively, vessels will need to be equipped with scrubbers to reduce emissions of SO_x.

Tracking progress

In its current form, the EEDI mandates a 1% annual improvement in the efficiency of the global fleet from 2015 to 2025.[6] According to IEA statistics and United Nations Conference on Trade and Development (UNCTAD) activity data, the energy used by the global shipping fleet per tonne kilometre declined by 2.2% between 2000 and 2014.[7] This suggests that the EEDI will prevent the backsliding of energy efficiency, but not the reduction of GHG emissions beyond historical trends. Fuel price increases due to the sulphur cap could stimulate interest in efficiency and reduce energy use, but technologies that reduce SO_X emissions – except for advanced biofuels, low-carbon synthetic fuels and, to a much lesser extent, LNG – will not lower GHG emissions.[8]

Getting on track with the 2DS requires an annual efficiency improvement of 1.9% MJ per vehicle kilometre (MJ/vkm), and 2.3% MJ per tonne kilometre (MJ/tkm), between 2015 and 2025. This can be achieved by exploiting the efficiency improvement potential for new and current ships and the adoption of operational improvements. Efficiency technologies available today could roughly halve the average fuel consumption per vehicle kilometre of new ships (IEA estimate based on Smith et al., 2016). This will need to be complemented by the use of advanced biofuels.[9]

Recommended actions

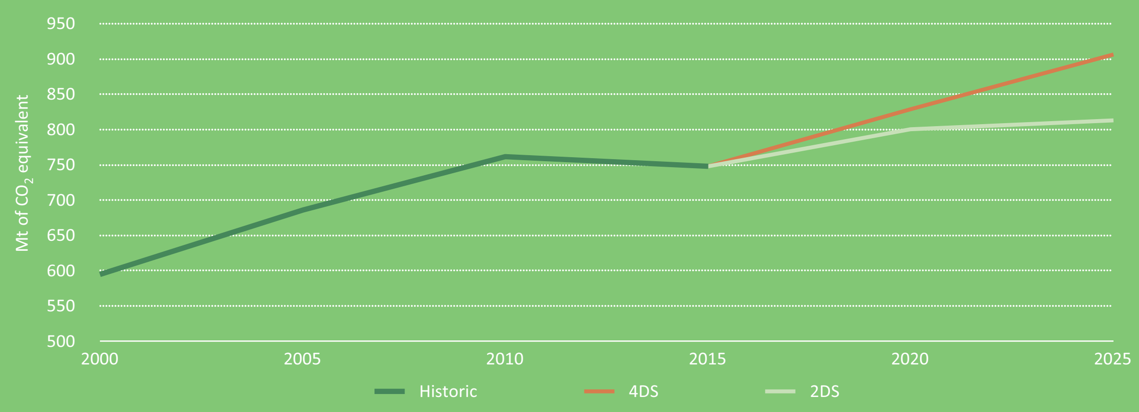
Defining a GHG emissions mitigation target for international shipping is a first step to getting on track with 2DS targets.[10] Raising the ambition of the EEDI, introducing mandatory standards on operational efficiency (also requiring proper monitoring of ship performances) and pricing GHG emissions are effective instruments to move in this direction.

The International Maritime Organisation (IMO),[11] is the major forum in which this vision can be developed and implemented. Proactive action in the IMO is paramount to successfully reduce GHG emissions from international shipping.

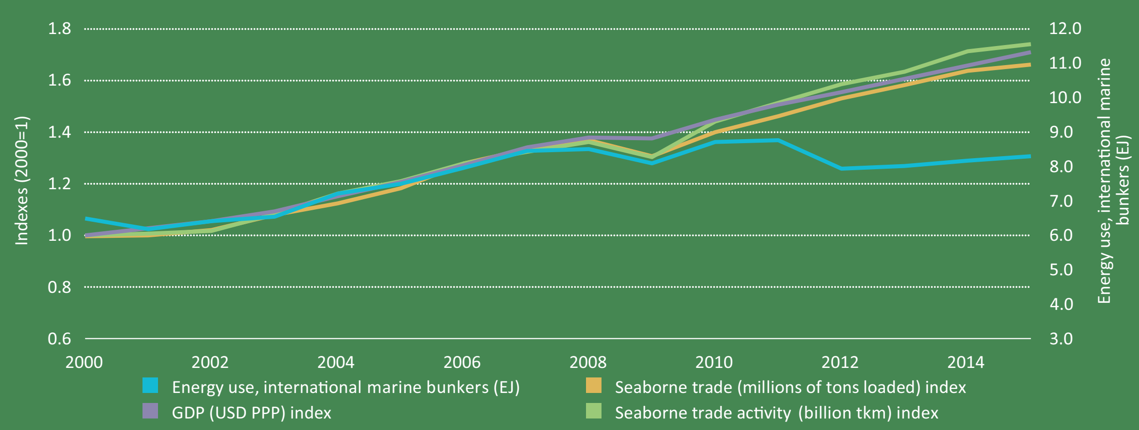
Long-term investment decisions will have to be taken by ship owners, operators, financiers and refiners to reduce local pollutant emissions. In the absence of rapid signals to steer these decisions towards GHG emissions reductions goals, investments aiming only to reduce only local pollutant emissions will run serious risks to be stranded when pressure on shipping to contribute to the low-carbon transition will grow.[12]

1-12. Refer to Technology overview notes on page 102.

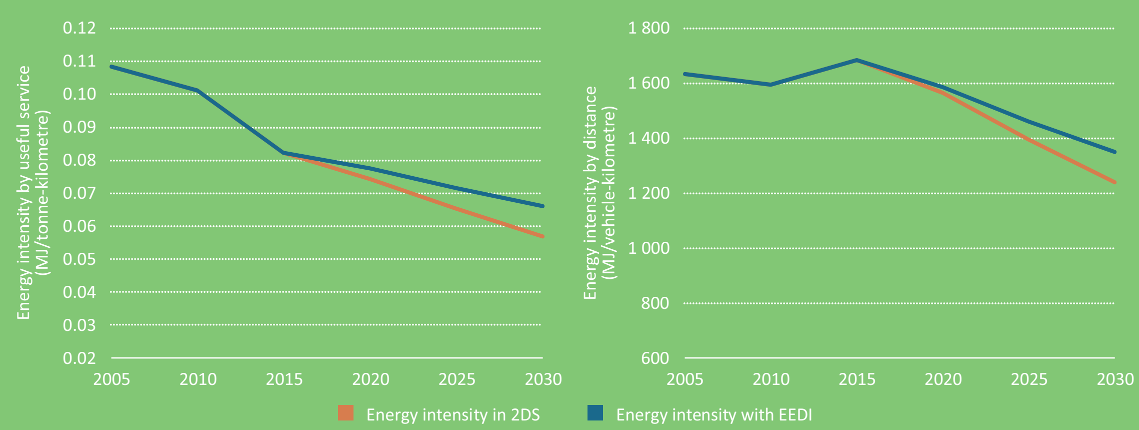
37 International well-to-wake shipping CO_2-eq emissions trajectories



38 Development of seaborne trade, global GDP and energy use



39 Energy intensity development under current regulation and 2DS



For sources and notes see page 102

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

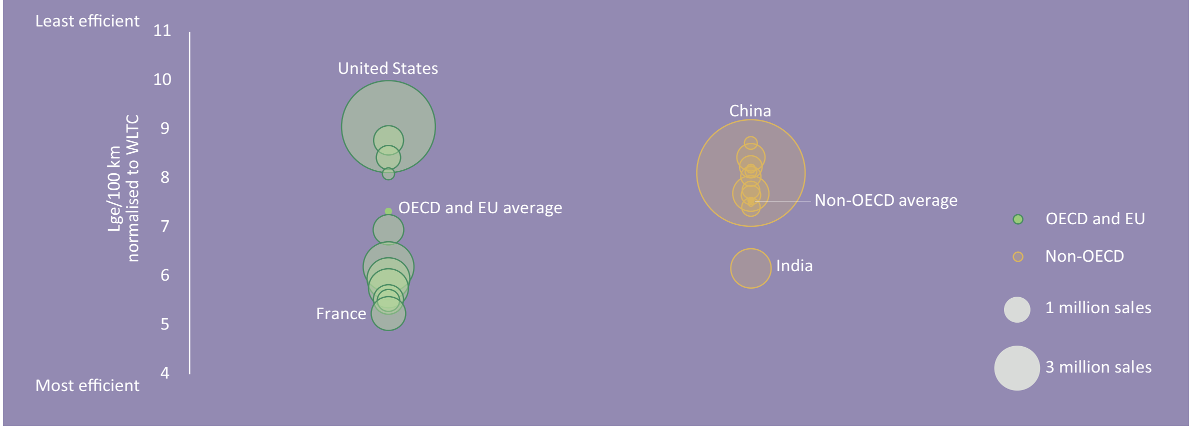
Despite good progress over the past decade in the geographical coverage of countries using fuel economy policies, progress in fuel economy improvement is clearly lagging what is needed for the 2DS. Realigning the development of fuel economies with the GFEI objective is possible with the adoption of policies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

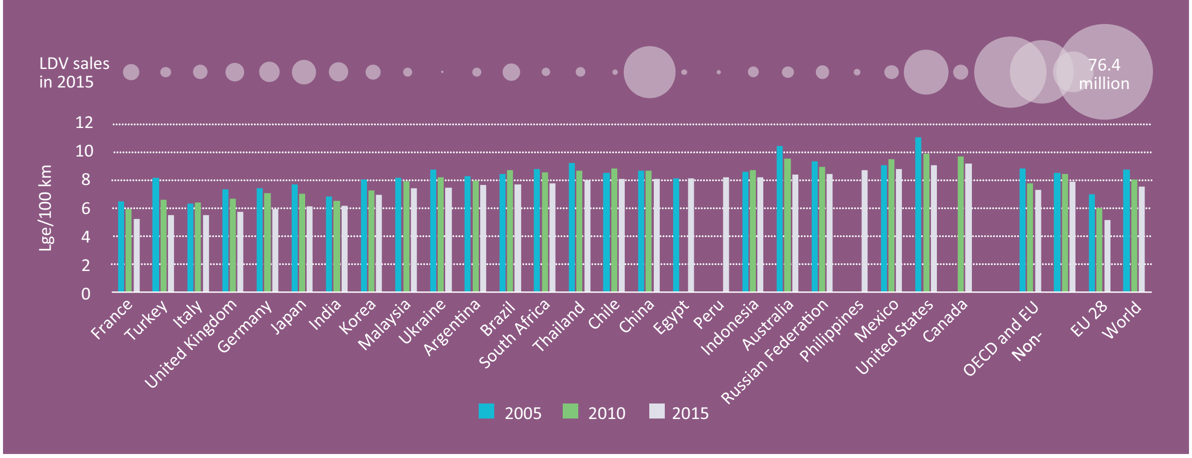
Reducing the gap between tested and on-road fuel economy is essential to meet 2DS targets. This goal requires more ambitious implementation procedures and the monitoring of fuel economy regulations, such as the WLTP, that better reflect real-world vehicle operation. Achieving increased accuracy in real 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 103.

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



41 Fuel economy development, test values, 2005-15



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

For sources and notes see page 103

Transport biofuels

Not on track

Positive developments

Global biofuel[1] production increased to around 137 billion L (3.3 EJ) in 2016. Conventional biofuels are on course to meet 2DS targets for 2025; however, accelerated production of advanced biofuels is necessary to meet 2DS needs for transport sector decarbonisation.

Recent trends

In 2016, conventional biofuels accounted for around 4% of world road transport fuel. Double-digit global production growth pre-2010 slowed to a modest 2%[2] y-o-y, due to structural challenges and policy uncertainty in key markets.

In the United States, ethanol output is anticipated to stabilise due to lower investment in new capacity and reaching the corn ethanol limit within the Renewable Fuel Standard. Meeting Brazil's 2030 commitment to reach an 18% share of sustainable biofuels in its energy mix would equate to over 50 billion L of fuel ethanol demand, but accelerated production growth will be required if this goal is to be met. Biodiesel policy support remains robust in both countries, with production growth expected.

In the European Union, proposals for the revised Renewable Energy Directive (RED) covering 2020-30 include a scale-down of the cap on food crop-based biofuels from 7% to 3.8% (by energy) of the 2030 renewable energy target. Conversely, in Asia many petroleum product-importing countries have enhanced policy support for domestically produced biofuels, boosting markets for ethanol (e.g. India and Thailand) and biodiesel (e.g. Indonesia and Malaysia).

Advanced biofuel projects have been announced in a growing number of countries, including China, India and Thailand. Evidence also exists of strengthening advanced biofuel policy support, particularly in Europe where the aforementioned proposals for a revised RED specify an increase in the advanced biofuel share of transport energy demand from 0.5% in 2021 to 3.6% by 2030. In addition, with a growing number of commercial flights and fuel off-take agreements, aviation biofuels are poised to play a central role in the aviation industry's long-term decarbonisation plans.

Tracking progress

Conventional biofuels are on track to meet volumes required by the 2DS for 2025. For advanced biofuels, full delivery of the project pipeline, combined with a scale-up in output towards rated capacity at commissioned plants, could deliver around 2.3 billion L (0.6 EJ) in 2020, although this level would be less than 1.5% (by volume) of total forecast biofuels production. Consequently, a twenty-five-fold scale-up in production would be necessary over 2020-25 to achieve the 57 billion L (1.6 EJ) advanced biofuels contribution to the 2DS in 2025. This projection highlights that significantly accelerated commercialisation is needed to keep pace with 2DS requirements.

Recommended actions

Stable and long-term policy frameworks can facilitate expansion of the advanced biofuels industry and enable capital and production cost reduction potential. Ambitious national transport sector targets for emissions reduction, shares of renewable energy or, as in Sweden, phasing out fossil fuels provide a favourable investment climate. These frameworks can include sub-targets for the road freight, marine and aviation sectors, which are more difficult to decarbonise.

More widespread advanced biofuel mandates will be essential to accelerating uptake. Alternatively, legislation to stipulate defined reductions in the life-cycle carbon intensity (CI) of transportation fuels (e.g. as established in California and Germany) stimulates demand for biofuels with the highest emissions reduction potential.

These policies can be complemented by financial de-risking measures to support investment while costs remain high, tax incentives, and financial mechanisms to facilitate technological innovation and commercialisation. Policies to expand flexible-fuel vehicle fleets and biofuel distribution infrastructure will also support market growth. For aviation biofuels, supply chain development and measures to reduce cost premiums over fossil jet fuels are needed.

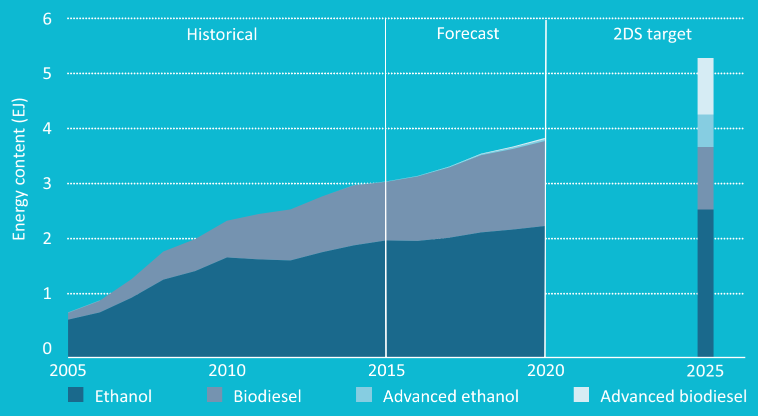
The recent launches of the Biofuture Platform and Below50 initiative are anticipated to facilitate an enabling environment for sustainable biofuels through enhanced international collaboration. Biofuels market expansion must respect environmental, social and economic sustainability considerations via industry benchmarking against recognised sustainability indicators and through the presence of strong governance frameworks.

1-2. Refer to Technology overview notes on page 103.

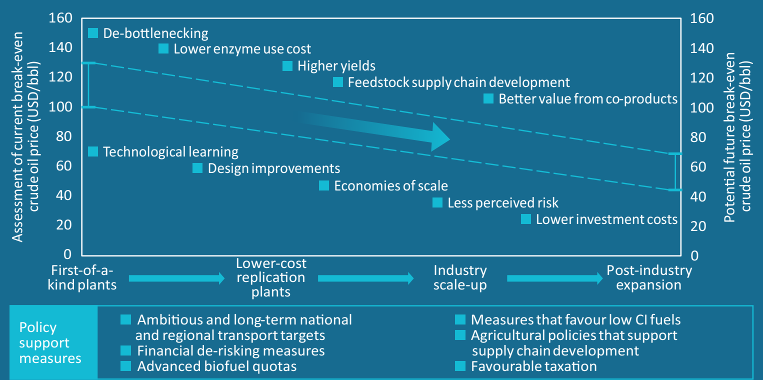
24%

AVERAGE ETHANOL BLEND BY 2026 SPECIFIED WITHIN THAILAND'S ALTERNATIVE ENERGY DEVELOPMENT PLAN

43 Global biofuels production



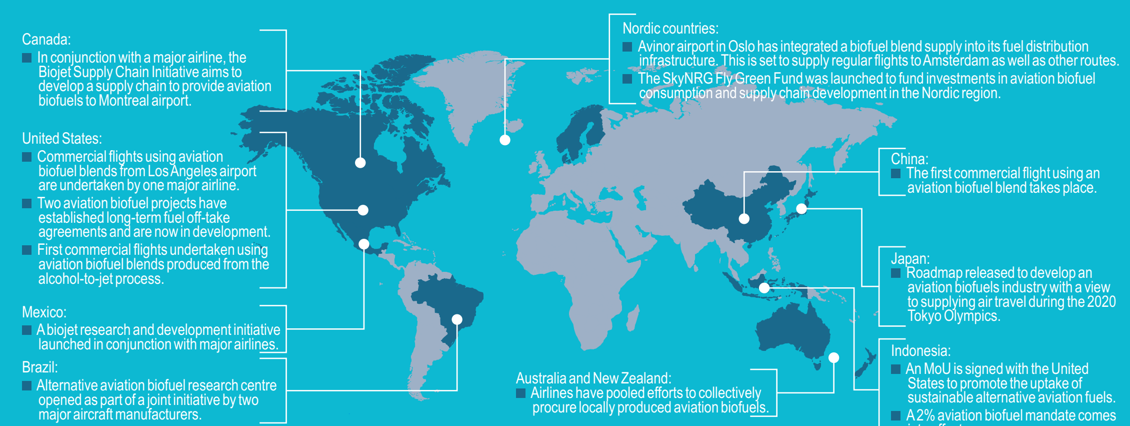
44 Cellulosic ethanol cost reduction potential



5

COMMERCIAL SCALE CELLULOSIC ETHANOL PROJECTS ANNOUNCED FROM INDIAN STATE OIL MARKETING COMPANIES

45 Global aviation biofuel developments over 2015-16



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For sources and notes see page 103

Buildings

● Not on track
↗ Positive developments

A growing number of countries have put in place policies to improve building energy performance, but average energy consumption per person in the global buildings sector still remains practically unchanged since 1990. Assertive action is needed now across all countries to improve global average energy use per capita by at least 10% by 2025 using energy-efficient and low-carbon building technologies.

Recent trends

Global building-related CO_2 emissions have continued to rise by nearly 1% per year since 2010. Coal and oil use in buildings has remained fairly constant since then, while natural gas use grew steadily by about 1% per year. Global use of electricity in buildings grew on average by 2.5% per year since 2010, and in non-OECD countries it increased by nearly 6% per year. That growth is significantly faster than the 0.5% average annual improvement in global CO_2 intensity per kilowatt hour of electricity since 2010.

Global buildings sector energy intensity (measured by final energy per square metre) fell by 1.3% per year between 2010 and 2014, thanks to continued adoption and enforcement of building energy codes and efficiency standards. Yet progress has not been fast enough to offset growth in floor area (3% per year globally) and increasing demand for energy services in buildings.

More telling is energy demand per capita, where global average building energy use per person has remained practically constant since 1990, at just less than 5 MWh per person per year. In OECD countries, average energy consumption per person started to fall from a peak of 12 MWh in 2010, but this decline may be partly explained by warmer winters in recent years, as space heating accounts for 45% of OECD building final energy use. In non-OECD countries, average building energy use per capita continued to grow by around 1% per year since 2000.

To meet 2DS targets, average building energy use per person globally needs to fall by at least 10% to less than 4.5 MWh by 2025. OECD countries in particular need to shift away from historical trends and bring average energy use per capita below 1990 levels through rapid energy efficiency action. In non-OECD countries, where energy access and economic development are equally important priorities (among others), effort is needed to deploy energy-efficient and low-carbon building technologies to meet a rapidly growing demand for energy services without following an unsustainable pathway towards high building energy consumption per person.

Tracking progress

Current policies and investments in building energy efficiency are not on track to achieve 2DS targets. Nearly two-thirds of countries still do not have any building energy codes in place. A similar share of energy-consuming equipment in buildings globally is not covered by mandatory energy efficiency policies.

Some progress towards realising the untapped potential in the global buildings sector has been seen since the Paris Agreement in 2015. Nearly 90 countries have registered building actions in their NDCs. More than 3 000 city-level and 500 private sector building commitments have also been registered under the United Nations Framework Convention on Climate Change. A number of industry and professional bodies have also mobilised to support market development of high-performance buildings, including initiatives to implement net-zero/carbon-neutral building programmes.[1]

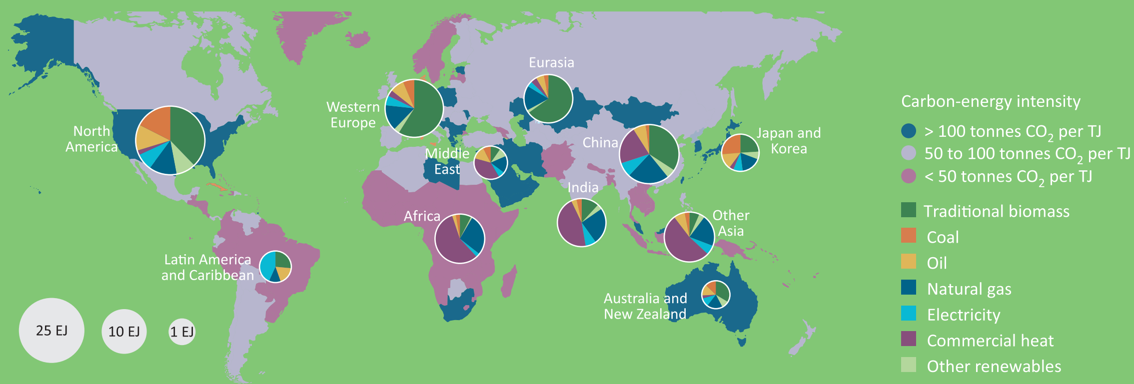
Recommended actions

Concerted global effort is needed to rapidly expand, strengthen and enforce building energy policies across all countries to prevent the lock-in of long-lived, inefficient building investments. Transitions to a 2DS pathway will require clear and consistent signals, along with incentives and appropriate financing mechanisms, to drive consumers and manufacturers to maximise energy efficiency opportunities. Educational programmes, training and capacity building, and better building energy data can also help improve energy efficiency policy design, adoption and enforcement.

Significant effort is needed in the coming decade to leapfrog best practices and high-performance technologies to developing countries. Greater access to finance is also critical to increase efficiency investments in both non-OECD and in OECD countries. Lastly, much greater effort is needed to address energy performance of existing buildings, especially in OECD countries.

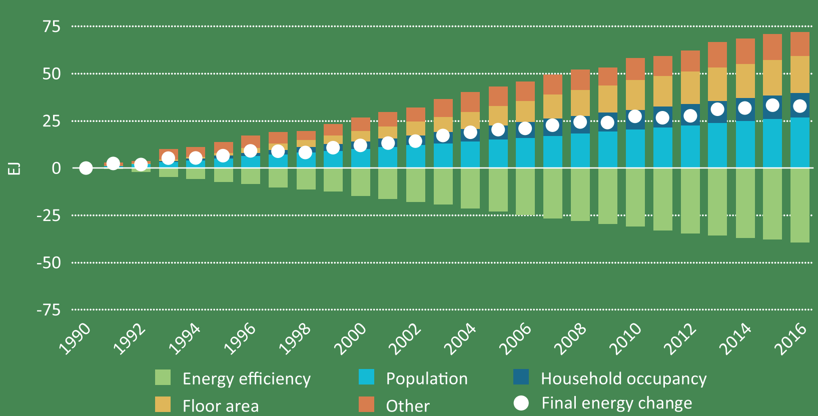
1. Refer to Technology overview notes on page 104.

46 Buildings energy use by fuel



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.

47 Decomposition of final energy demand



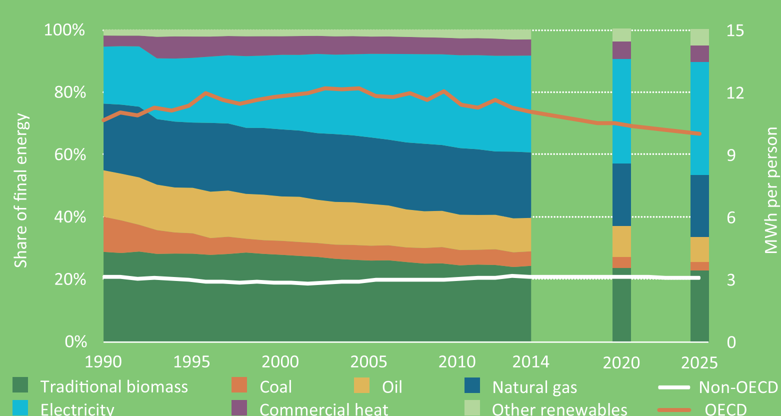
45%

INCREASE IN BUILDING-RELATED EMISSIONS SINCE 1990

10%

OR MORE IMPROVEMENT IN GLOBAL BUILDING ENERGY PERFORMANCE PER PERSON BY 2025

48 Final energy use by fuel and per person



For sources and notes see page 104

Building envelopes

● Not on track
~ Limited developments

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]

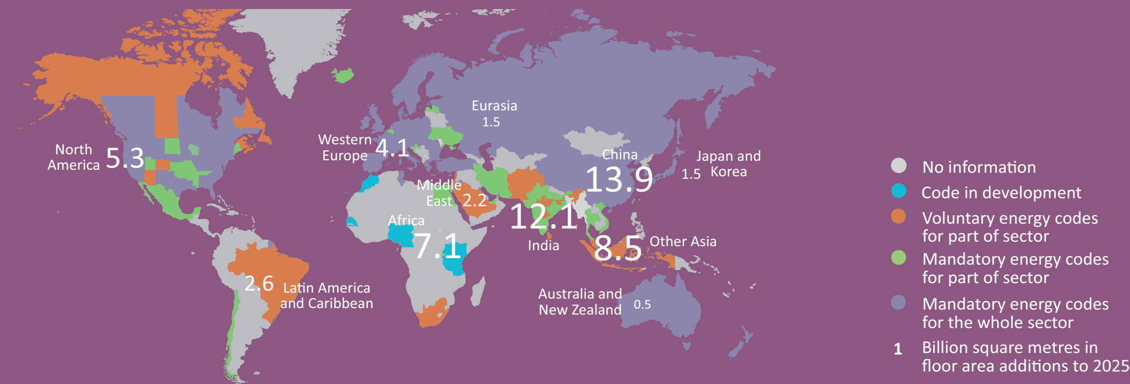
Recommended actions

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.

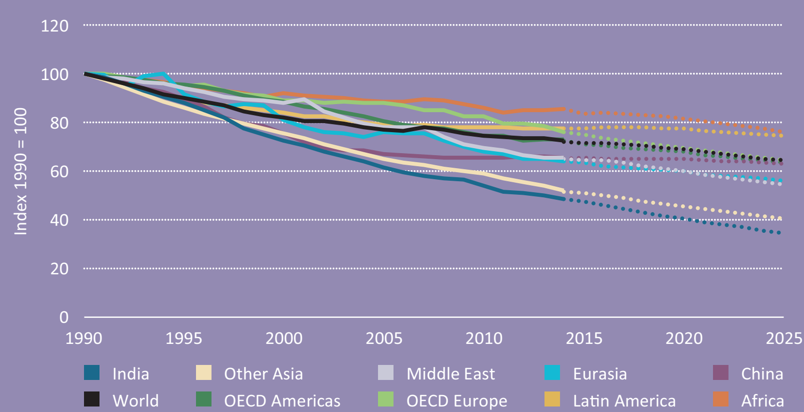
1-2. Refer to Technology overview notes on page 105.

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.

50 Change in building envelope performance



ONLY

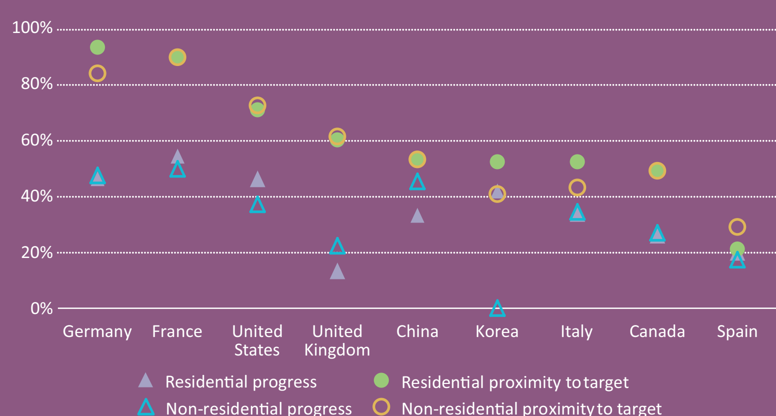
1/3

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

51 Efficiency policy progress, 2005-15



For sources and notes see page 105

Lighting, appliances and equipment

● Not on track
↗ Positive developments

The global energy efficiency potential from lighting, appliances and equipment in buildings represents 100 EJ of energy savings potential to 2025. Action is needed to expand energy efficiency standards and labelling (S&L) programmes across all countries and the vast majority of products. S&L programmes also need to evolve with technology developments to ensure continual energy efficiency improvements.

Recent trends

Global energy use for lighting, appliances and equipment[1] in buildings grew steadily at 1% per year since 2010. In non-OECD countries, where demand for energy services and thermal comfort is growing rapidly, the energy use grew at twice that rate.

Energy demand for lighting and space cooling in buildings grew considerably over the last decade, particularly as improved access to electricity, increasing household wealth and demand for thermal comfort all drove greater energy demand in developing countries. Globally, cooling and lighting demand both grew by roughly 2% per year since 2005, while in non-OECD countries the average annual growth rate was more than 5%.

Increasing ownership of household appliances (e.g. refrigerators and televisions) and changes in consumer preferences (e.g. appliance size) also continued to drive greater energy use in buildings. Despite considerable progress on S&L policies for household appliances in many countries, when population growth, decreasing household size[2] and growing access to electricity in developing countries are taken into account, the net effect is that major appliance energy demand globally grew by 50% between 1990 and 2016.

By contrast, space heating and hot water energy demand grew at a slower pace of less than 0.5% per year since 2010. This lesser rate is due in part to shifts away from traditional use of biomass in non-OECD countries, while energy efficiency progress (e.g. condensing boiler and heat pump adoption in many OECD countries) also helped to improve energy demand in those end uses.

Tracking progress

Coverage of S&L programmes continues to expand across more countries and an increasing number of products, but assertive policy across all countries is needed to expand and strengthen S&L across the vast majority of building end uses.

Effort is also needed to address energy efficiency and product labelling for networked devices and other electrical plug loads (e.g. portable electronics and small appliances), which grew on average by 3.5% per year since 2010. “Smart” appliances and networked devices may represent a major energy efficiency opportunity, but work is still needed to ensure those technologies are used smartly and to their energy-saving potential.

Much greater effort is also needed to address cooling energy demand growth globally. Despite minimum performance standards and availability of high-efficiency products, the average energy performance of cooling equipment is still very similar across most countries and continues to underperform. Much greater effort is needed to capture the energy efficiency potential, especially in rapidly growing markets such as India, Mexico and Indonesia, where cooling demand could increase by 5% or more per year over the next decade.

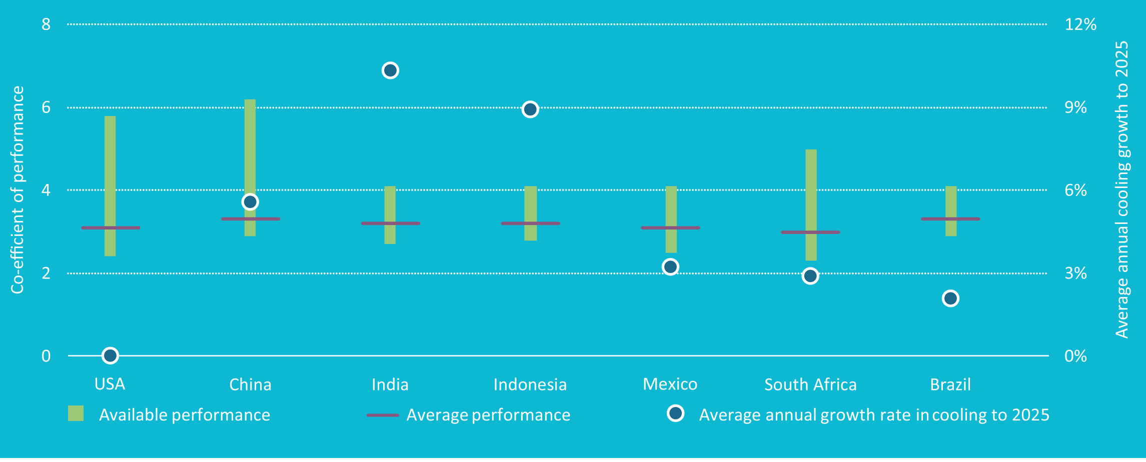
On a positive note, lighting sales, despite earlier shifts from inefficient incandescent lamps to equally inefficient halogen lighting, started to shift to high-efficiency LEDs, which represented 15% of total residential lamp sales in 2015 (expected to have grown to nearly 30% in 2016). Recent market trends also suggest that average television energy use started to peak in 2015, with energy efficiency improvements moving faster than increases in television sizes.

Recommended actions

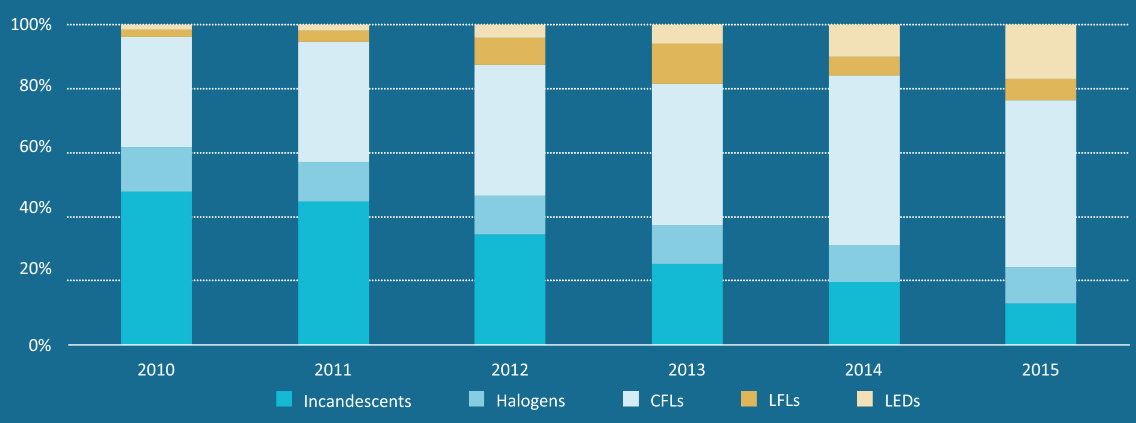
Global building electricity consumption needs to be halved from the current 3% increase per year over the last decade to a 1.5% annual increase under the 2DS. S&L programmes need to be expanded and strengthened across all countries and the vast majority of end-use products. They also need regular review to ensure that efficiency requirements keep up with changes in technology and are in line with 2DS objectives. This review includes monitoring and enforcement of existing S&L. Last, S&L programmes should seek to account for changing consumer preferences (e.g. greater image resolution) that can have a significant influence on final energy demand.

1–2. Refer to Technology overview notes on page 105.

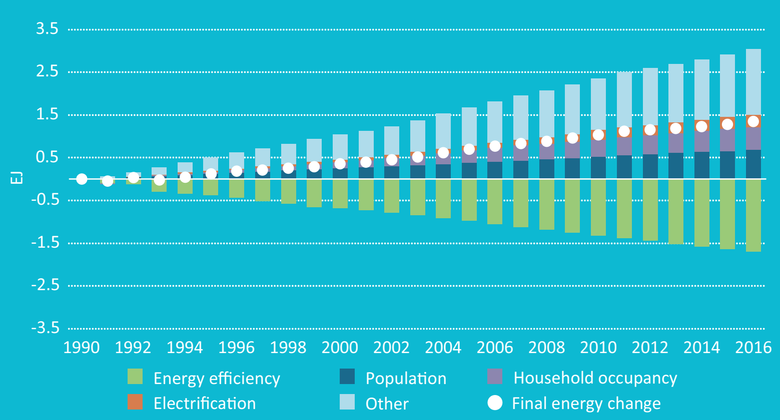
52 Efficiency ratios of split-package air conditioners, 2015



53 Global lighting sale share estimates in the residential sub-sector



54 Final energy decomposition of major appliances



50%

REDUCTION IN AVERAGE ANNUAL ELECTRICITY DEMAND GROWTH FOR LIGHTING, APPLIANCES AND EQUIPMENT NEEDED BY 2025

For sources and notes see page 105

Renewable heat

● Not on track
~ Limited developments

Heat accounts for more than 50% of final energy consumption and remains largely fossil fuel-based. Growth in renewable heat has been steady but slow, and an increase of 32% would be needed between 2014 and 2025 to meet 2DS goals. Solar thermal heating would need to see the largest increase, but if its recent slowdown in growth continues, it will not be on track.

Recent trends

The direct use of renewables for heat (modern biomass, solar thermal and geothermal) increased by 8%, from 13.2 EJ in 2010 to 14.2 EJ in 2014.[1] More than one-third of this increase was due to the consumption of renewable heat in China, mostly through the rapid growth of solar thermal installations. Currently, the European Union is the largest consumer of renewables for heat, with almost 15% of its heat demand met by renewables. In the emerging economies, Brazil has one of the highest shares of renewables used for heat (37%), due to using biomass in industries such as food, paper and pulp, and ethanol.

Biomass (excluding the traditional use of biomass) accounts for 90% of renewables used for heat, with a variety of heat applications in the buildings and industry sectors. Biomass use for heating in the European Union has grown steadily and accounted for over 60% of all wood pellet demand in the European Union in 2015. However, some evidence indicates that low heating oil and LPG prices have constrained the growth of biomass heating in some countries, especially in the off-the-gas-grid segment where biomass tends to be most competitive.

Solar thermal (mainly used for water heating) has increased more rapidly than renewable heat as a whole. However, the rate of new installations has slowed in the last two years due to a slowdown in China and sluggish growth in the European Union. In 2015, the total newly installed capacity was 40 gigawatts thermal capacity (GW_{th}), 15% lower than in 2014. In countries with high levels of insolation, solar thermal systems can be very cost-competitive with electric or fossil fuel alternatives. Elsewhere, large installations can provide economies of scale. The world's largest solar thermal plant entered operation in Silkeborg in Denmark at the end of 2016 and is expected to produce 80 000 MWh for use in the local district heating network.

Electric heat pumps also play an important role in heat decarbonisation, through the use of renewable heat stored in the ground, air and water and the rising share of renewables in electricity supply. Heat consumption from heat pumps is estimated to have increased by 7% since 2010, with the fastest growth (50%) in China.

Tracking progress

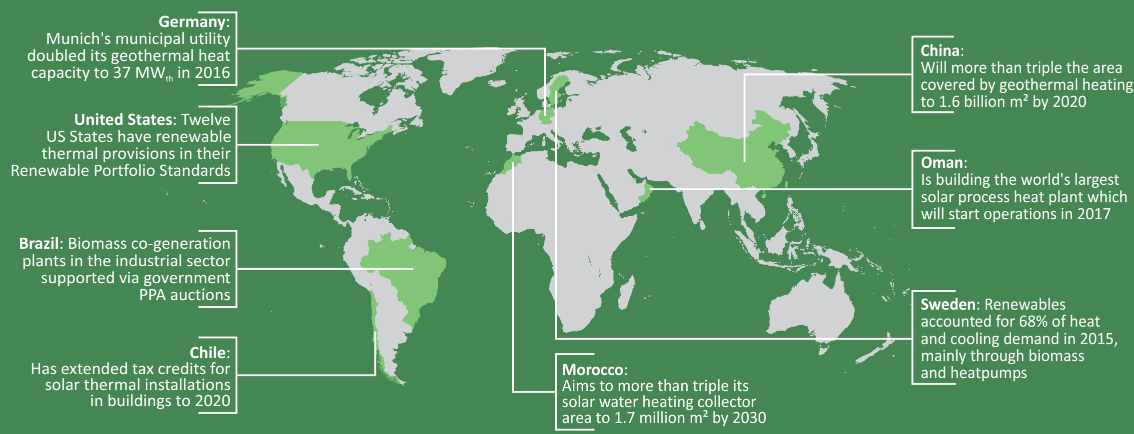
Good potential exists globally for renewable heat, but remains largely unexploited. Growth in renewable heat has not matched that of renewable electricity. The direct use of renewables for heat would have to increase 32% between 2014 and 2025 to meet the 2DS target, with faster growth needed in the non-biomass segments.[2,3] For example, solar thermal heat consumption would have to almost triple by 2025. This growth would require an annual deployment rate more than twice that of current levels. Achieving that level is unlikely unless deployment in key countries, including China and India, picks up. Heat pump use would also have to increase more rapidly than in recent years, coupled with rapid deployment of renewable electricity.

Recommended actions

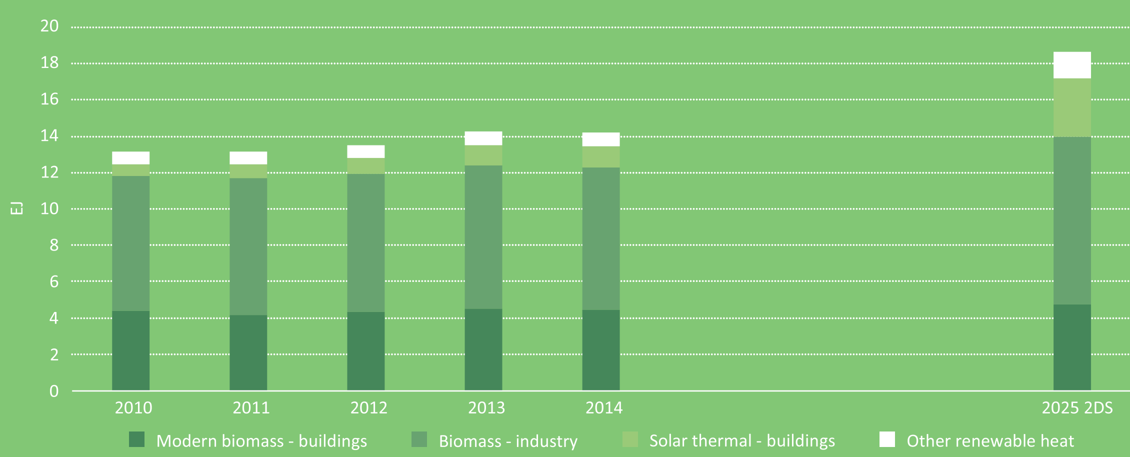
Renewable heat continues to face numerous economic (e.g. high capital costs, split incentives, and fossil fuel subsidies) and non-economic (e.g. lack of awareness, lack of confidence, and suitability issues) barriers. To address these barriers, increased policy support and policy consistency are needed. Governments should set targets and develop strategies for heat decarbonisation. To be effective, these need to cover all sectors and consider the appropriate balance between renewable heat deployment, heat electrification and energy efficiency improvement. An expansion of district heating networks can also play a role, allowing economies of scale to be exploited, as well as better control of air pollutants in the case of biomass. Due to the fragmented and decentralised nature of heat supply, heat planning at the local level can make an important contribution. Other policy instruments that have been shown to be effective include carbon taxes, building codes that require renewable heat installations in new buildings, and financial support mechanism.

1-3. Refer to Technology overview notes on page 106.

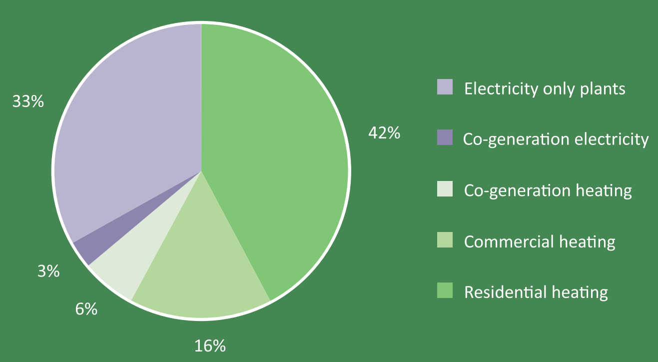
55 Renewable heat



56 Renewable heat by technology 2010-14 versus 2025 2DS target



57 Share of EU wood pellet consumption (2015)



SOLAR THERMAL CAPACITY REACHED

436 GWth

IN 2015

For sources and notes see page 106

On track
↗ Positive developments

Energy storage

Strong deployment of storage technologies continued to be driven by policy, technological developments and a better appreciation by regulators of the value of storage. Lithium-ion batteries are positioned as the main storage technology due to cost reductions and rapid scale-up of manufacturing capacities. Storage is on track with 2DS due to positive market and policy trends, but an additional 21 GW of capacity is needed by 2025. Further policy action is, therefore, required to tackle challenges to deployment.

Recent trends

With the rise of renewables in much of the world, understanding and managing flexibility is becoming a cornerstone of energy markets. Energy storage played a much greater role in providing flexibility in 2016, with important deployments in both short-term and long-term balancing markets, particularly in Europe and the United States.

While the total capacity additions of non-pumped hydro utility-scale energy storage grew to slightly over 500 MW in 2016 (below the 2015 growth rate), nearly 1GW of new capacity was announced in the second half of 2016. The vast majority of utility-scale stationary energy storage capacity in 2016 was lithium-ion batteries. Other batteries (e.g. redox flow or lead-acid) amounted to an estimated 5% of capacity additions, with all other storage technologies combined accounting for the remaining 5%. A key defining trend during 2016 was the concerted action of integrated energy companies, manufacturers and equipment providers to expand their storage activities, leading to a more concentrated market.[1]

Energy storage in the United States experienced a slight growth contraction relative to 2015, with activity largely sustained by state policy. In Europe, growth continued at historic rates, with a capacity market auction in the United Kingdom delivering half a gigawatt of winning bids. Countries with significant solar PV capacity (France, Germany, Australia and Italy) led growth in the nascent market for behind-the-meter storage installations.

In China, the 13th FYP, the trend toward high-voltage transmission capacity and the lack of specific policy support weaken the outlook for battery storage and strengthen that of large-scale pumped hydro projects. Commissioned storage installations in the ASEAN region, however, almost doubled, largely driven by small-scale and island systems.

Beyond the technologies themselves, innovative business models that capitalise on the benefits of storage have seen timid growth in some regions. While there are positive moves by regulators in Europe and in the United States to create enabling environments for aggregators, virtual power plants and other platforms, it is still early to evaluate their impact on 2DS projections.

Tracking progress

The 2DS envisions 21 GW aggregate energy storage capacity by 2025. The key area of uncertainty remains behind-the-meter storage. Growth in this area was significant in 2016, albeit from a very low base of 20 MW and regulatory uncertainty subduing outlook.

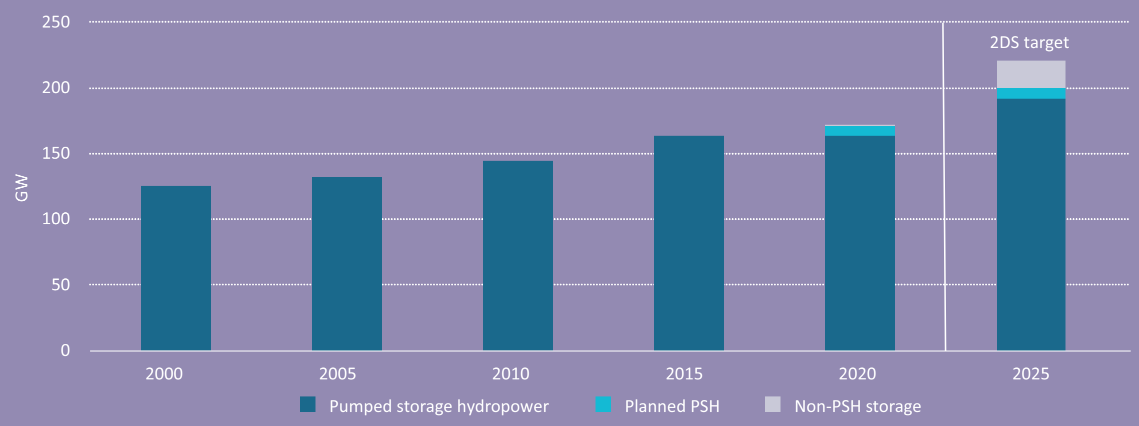
Remaining on track with the 2DS targets will require the technology growth to continue at the current growth trajectory over the next decade. While evolutionary improvements to the technology appear to be sufficient to meet short-term deployment needs, advanced technologies, particularly those decreasing material requirements and increasing energy density, will be required to stay on track. In 2016, larger players began to acquire start-ups that are developing these next-generation technologies.

Recommended actions

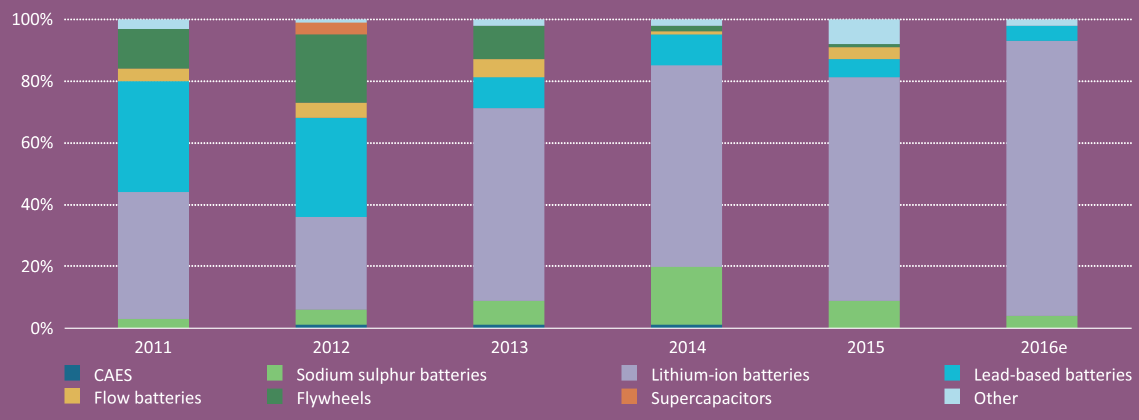
Coherent policies need to complement promising technological developments to fully realise the potential of energy storage. The use of storage by grid operators is limited at present, largely due to the lack of clarity and transparency in market rules and regulations, the lack of markets for flexibility and ancillary services, and the low penetration of new business models. While net metering and other incentives can have a positive impact on behind-the-meter storage, policy assessments are required in each jurisdiction to assess the impact of prosumer-generated electricity and storage. This includes an appreciation of the impact of such developments on traditional grid and utility business models.

1. Refer to Technology overview notes on page 106.

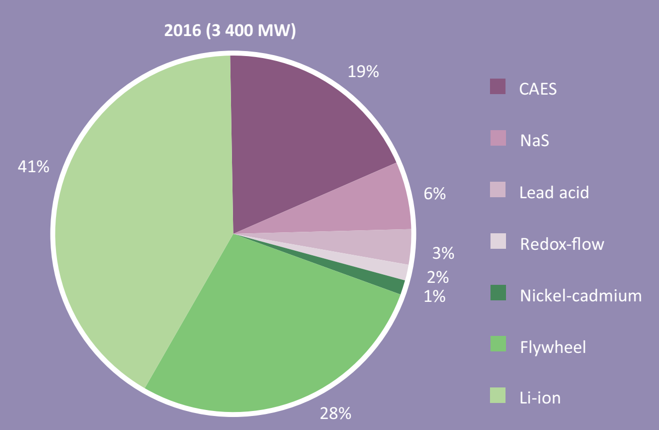
58 Globally installed electricity storage (GW)



59 Growth in non-pumped hydro storage technology deployment



60 Lithium-ion has grown to dominate non-pumped hydro storage



For sources and notes see page 106

Tracking Clean Energy Innovation Progress

Tracking clean energy innovation progress

Key messages

- The total investment in clean energy RD&D is estimated to have been USD 27 billion in 2015 but is not yet rising globally. It needs to pick up to be on track toward a sustainable energy transition. Public funding of clean energy RD&D, including by certain state-owned enterprises, was over USD 19 billion in 2015. This is significantly higher than combined corporate RD&D expenditure of USD 6 billion and investment by venture capital funds into start-up clean energy technology companies of around USD 2 billion in 2016.
- Clean energy RD&D has been key to provide us with the clean technology options of today, and will continue its importance into the future. Public funding is striving to fulfil its prescribed function of supporting technologies that are further from the market or have high development and demonstration costs, including nuclear, CCS and ocean energy. Corporate investment into clean energy is growing but remains a small share of total corporate energy sector R&D, which is dominated by companies active in oil and gas, thermal power, networks and utilities. Venture capital funds, on the other hand, are mostly targeting clean energy topics.
- Implementation of complementary public and private pledges, such as Mission Innovation and Breakthrough Energy Coalition, can serve as essential springboards to boost clean energy innovation. Such new efforts can benefit from building upon existing collaboration mechanisms such as IEA's Technology Collaboration Programmes.
- Understanding RD&D investment patterns can further enhance the effectiveness of RD&D spending as well as highlight areas for collaboration. Key recommendations for decision makers in governments and the private sector include:
  - Collect better data on public- and private-sector RD&D spending, especially for key emerging countries and the private sector. Better data will enable public and private decision makers to better identify gaps and to enhance efficiency of resource allocation.
  - Develop and track key performance indicators for priority technologies. Measurement of progress in clean energy innovation needs to go beyond the flow of money and to also focus on performance indicators, such as those defined in IEA Technology Roadmaps.
  - Increase further the level of collaboration and exchange on innovation policy, including through use of innovative public-private partnerships, including Mission Innovation, and IEA Technology Collaboration Programmes (TCPs). Further explore how international co-operation across the public sector can leverage private-sector engagement.
  - Enhance communication of progress in technology innovation not only to stimulate further discussion among experts, but also unlock additional investment opportunities.
  - Conduct clean energy RD&D investment in concert with the other key elements of the innovation ecosystem, including early-stage market development and human resource capabilities. Effective priority setting and investment takes account of short-term and long-term perspectives and all relevant levels of activity: international, national, municipal, company and entrepreneur.

Introduction

Technological innovation has always been a key driver of energy sector evolution. The importance of innovation will only increase as societies strive to achieve affordable, secure and sustainable energy systems into the future. This is especially true where societies are aiming to achieve a number of shared energy policy objectives, such as climate change mitigation, air pollution and energy security.

The world's arsenal of clean energy technologies has been vastly improved since the first edition of *TCEP* was published in 2012. Many clean energy technologies are now cost-competitive, but innovation will need to be further accelerated in coming years. The individual sections of *TCEP 2017* highlight numerous areas in need of substantial technology[1] innovation. These areas range widely, from lignocellulosic biomass pre-treatment to low-energy CO_2 separation and compression, and from breakthrough cement production processes to small modular nuclear reactors and improved vehicle materials and design.

In addition to improving this suite of identified clean technologies, innovation can also take advantage of unforeseen opportunities. Options on a path to net zero emissions need to include certain "frontier" technologies that do not currently attract wide attention from investors, but that could be highly valuable over the coming decades.

Considering the inherently non-linear and uncertain nature of innovation, trying to assess incremental and radical innovations on a purely cost-benefit basis is misguided. Accordingly, governments should consider taking a portfolio approach to supporting public- and private-sector energy innovation (IEA, 2011). Such an approach balances the uncertainties of competing future scenarios with the potential payoffs of technological breakthroughs. It supports both lower-risk improvements to familiar technologies and more uncertain, potentially disruptive ideas.[2]

Moreover, truly innovative technologies – such as superconducting electricity transmission; cheap, dense hydrogen storage; novel low-impact construction materials; or fossil fuel-free iron and steel production – could help offset sectors and technologies that may underperform in achieving a 2DS, let alone a well-below-2DS. History shows that unimagined changes are more likely than unlikely over decades.[3] Looking back from 2070 may be like reflecting from today back to 1964, a time before pocket calculators, communication satellites and microwave ovens, let alone the Internet, drones and 3D seismic surveys.

This special feature section complements the main *TCEP* by focusing on RD&D, the first stage in the innovation journey (Box 2.1). It examines all the available public and private data on energy RD&D investment, including highlighting key trends. The special feature also includes a set of specific recommendations for governments and the private sector that take into account the complexities of the innovation process and its drivers. In the tables that follow this special feature, key technologies for each sector have been emphasised to draw attention to their RD&D progress and needs. The IEA will look to further build its competences in this area in going forward.

1. Technologies can be defined at various levels. At a high level, it could be the technology of space heating or even electrical space heating. At a lower level, a ground source heat pump refrigerant or borehole drill could be the focus for innovation. This report generally discusses technologies at their more aggregated level, recognising that they are composed of a vast number of smaller technologies that can be individually improved and contribute to overall progress.
2. A portfolio approach requires the following questions be answered by government sponsors: What technology improvements are central to realising the national vision of its energy future? Where might these improvements come from, and which policy instruments can deliver them most efficiently? What technologies could raise overall optionality value and keep open other visions that meet the policy objectives?
3. It hardly needs to be pointed out that energy technology innovation does not take place only in low-carbon energy technologies: traditional high-carbon energy technologies are also still being improved. Innovation in extraction technologies has made additional hydrocarbon resources available at economically viable costs – thereby dispelling the spectre of a near-term peak in oil production.

Box 2.1. Stages and sources of the innovation process

Innovation is an evolutionary process. Technologies are selected by users based on how well they fit the environment in which they arise.[4] Technologies that can adapt to the needs and resources of a greater number of users will be perpetuated, expanding their market share. As in the natural world, the selection environment itself is not static. Changes in related technologies, consumer behaviour or policy choice can iteratively improve the value of a given technology, making it more likely to be selected or – as has happened with fossil fuel infrastructure and will happen with some low-carbon technologies – displaced. Governments play a crucial role in shaping and influencing the marketplace for technologies.

The process of energy technology innovation can be represented in four stages (IEA, 2015):

- prototype and demo
- high cost and performance gap
- low cost and performance gap
- competitive without financial support.

At each stage the level of risk taken by investors is reduced, as is the need for public support. However, innovation is not usually a linear progression from prototype to demonstration, deployment and diffusion. A given technology is simultaneously at different stages in different markets and applications.[5] In addition, deployment will generate new ideas for improvements to a technology that will continuously appear at the prototype stage. Thus, the stages run concurrently and may overlap, feeding on one another and surpassing each other's performance (Figure 2.1).

At different stages of development, innovation arises from different sources, which means that support to technologies needs to be tailored accordingly. Four sources are identified:

- RD&D for novel technologies and improvements to existing technologies
- learning-by-doing, by which engineers and others improve technology incrementally as they get more experience
- scale-up of production enables economies of scale and efficient value chains
- exchange of knowledge between stakeholders across sectors and regions.

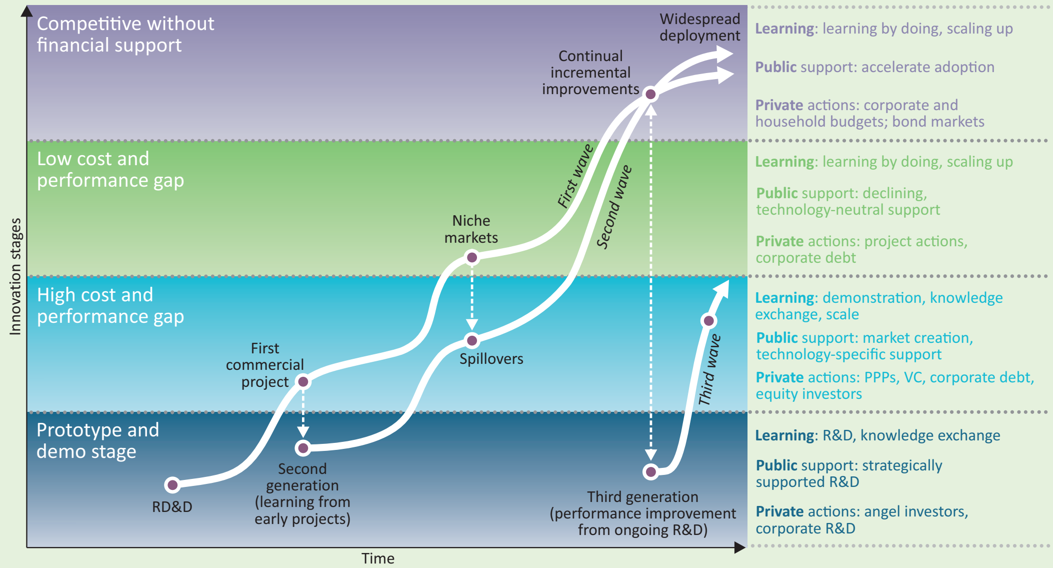
Through RD&D, new ideas and variants of existing technologies become available for selection. R&D precede demonstration and are undertaken in corporate research labs, universities, government research institutions and small firms. Demonstration in a real-world environment at commercial scale is a subsequent step to show technical and commercial viability. Demonstration informs market players and policy makers of cost and performance.

RD&D is mostly associated with the prototype and demo stage of the innovation process. At this stage, investors typically face the highest risks and government support is at its strongest. RD&D

4. The selection environment includes social norms, existing infrastructure, complementary technologies and competing technologies. Incumbent power and bounded rationality can influence these factors such that users may not always have the opportunity or information to be able to select optimal technologies, but among available options they tend to adopt solutions that fit their needs and expectations.
5. Today's batteries may be sufficiently low cost in island systems with high electricity prices, such as Hawaii, but in need of significant improvement or support in other US states.

however remains ongoing even when the technology is competitive without financial support to improve its performance and market competitiveness.

2.1. Figure: Stages of technology evolution and sources of innovation illustrated for solar PV



Key point: Innovation is an evolutionary process whereby today's commercial technologies – whether low-carbon or high-carbon – can be out-competed by solutions that are currently at the prototype stage if conditions are right.

Tracking RD&D spending

A centralised, reliable source for global energy RD&D spending data, either public or private, is not currently available. Government spending is a crucial source of innovation in the global economy (Box 2.2), yet the IEA is one of the few agencies collecting data on energy RD&D budgets, which its members report annually per technology category according to prescribed guidance. Outside IEA members, some countries publish budgets and expenditures, but generally they do not break down the data beyond broad classifications such as energy or electricity, oil and gas, and coal companies.

Furthermore, research into energy end-use efficiency is not always reported consistently, and so activity relating to efficient construction, vehicles or manufacturing is likely to be underreported (Wilson et al., 2012). Complicating the issue further, some countries have significant "public" investment in innovation beyond traditional government budgets. In China, as in some other countries, a significant share of government-directed research is performed by state-owned enterprises that fund their own RD&D. In Mexico, a duty is levied on the value of oil and gas production for spending on energy R&D by non-state entities (SENER, 2017). Separating research investments in "clean" energy from other energy topics is also troublesome and stakeholders have divergent definitions of what constitutes "clean".

Challenges are even larger in the corporate sector, with many companies hesitant to report their funding levels with any granularity. Furthermore, energy and non-energy RD&D spending are often difficult to distinguish.

With these challenges in mind, this special feature attempts to pull together in one place the available numbers, both for government and corporate spending, and to highlight key trends and opportunities to improve RD&D knowledge base.

Box 2.2. Stages and sources of the innovation process

Governments play a leading role in clean energy RD&D, especially because many societal benefits, such as reducing GHG emissions and local pollution are not yet sufficiently valued by markets. Through RD&D support, governments guide their economies towards activities they value as important. Governments thus have a dual role as a corrector of market failures and a shaper of market developments.[6]

Investments in RD&D are unlike other energy sector investments. The resulting assets are often intangible, and the returns are highly uncertain. Financers may have difficulty evaluating projects, especially if the only way to learn about a technology is to invest in it. Knowledge that is procured can be employed by competitors at low marginal costs. RD&D has long lead times and is often a collective, cumulative enterprise involving multiple organisations. Finance must be willing to bear high risks, be strategic and be patient.

While finance sources such as venture capital and private equity funds are successful at identifying technologies with high medium-term value, they have not been as successful as strategic long-term investors. Companies can access financial markets for major research projects, but investment can be limited by a vicious cycle: raising finance for research on a technology cannot be justified until a clear demand arises for the product; market actors cannot generate demand for the product until the technology is proven to be effective; the technology cannot be proven without finance for research. As a result, investments in innovation can be biased towards opportunities affording short-term gains: a survey of 240 000 small and large businesses undertaking energy R&D in the United States found that two-thirds of those that formally measure the economic impacts of their energy innovation expected to recoup investments within just two to three years (Anadon et al., 2011).

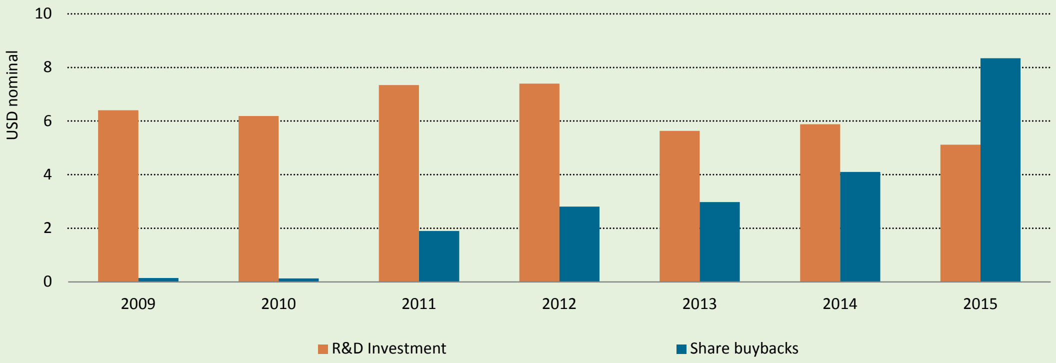
Corporate balance sheets are used for strategic investments in innovation, but evidence suggests that business expenditures may be becoming more focused on maximising short-term share value. Despite recent low interest rates for borrowing for R&D, many companies in Europe and the United States have raised finance for share buybacks.[7] Since the financial crisis, the level of share buybacks among companies active in clean energy technologies has risen and was higher than investments in R&D in 2015 (Figure 2.2). Furthermore, in industries dominated by incumbent players with substantial legacy assets, little incentive exists to support radical innovation, leading to a focus on incremental research.

6. Governments continually act to shape markets to realise social goods via actions such as: adjusting taxes, regulating market competition and antitrust behaviour, implementing trade and immigration rules, distributing revenues, providing access to education, prohibiting environmentally damaging activities, and creating forums for exchanging information.

7. Lazonick (2015) describes the impact of 1980s public policy in relation to share buybacks and its effect on the spending patterns of the US corporate sector since the objectives of maximising shareholder value have become dominant, leading to more short-term decision making.

Governments are a vital source of long-term, patient finance. Policy instruments can be used to enable access to finance for risky projects. As a result, much innovation by the private sector builds on publicly funded programmes for early-stage, higher-risk research (Mazzucato, 2011). Governments can “crowd in” other sources of funds in pursuit of long-term strategic missions. The commercial results of public energy RD&D investments can be dramatic. Within 20 years, China transformed itself from a technology importer into a major manufacturer and exporter of several low-carbon technologies (Tan and Seligsohn, 2010).

2.2. Figure: Expenditure on R&D and share buybacks of the top 20 clean energy firms by revenue



Note: Clean energy companies defined based on Bloomberg Industry Classification System (BICS) sectoral classifications.

Source: Bloomberg (2016), *Bloomberg Terminal*.

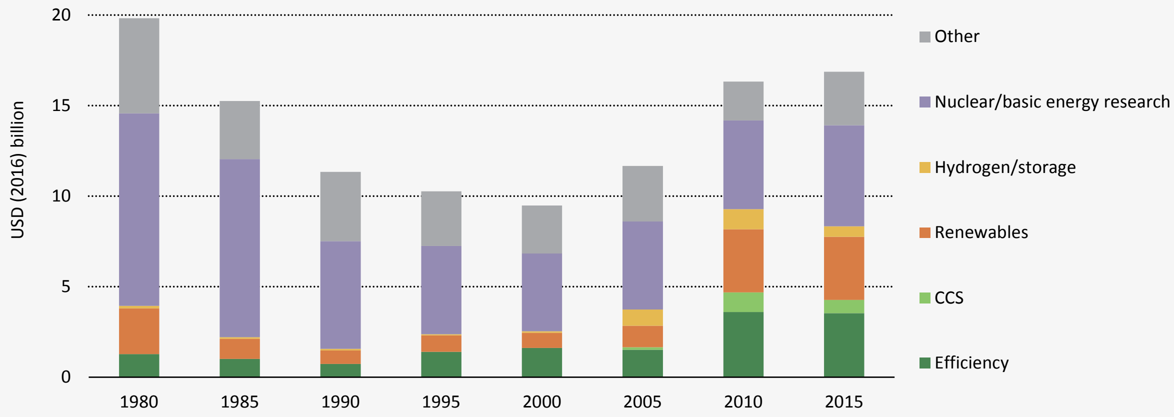
Key point: While access to capital has been relatively easy in recent years, some companies have been incentivised to spend on short-term benefits rather than their long-term development.

Trends in IEA member countries’ RD&D spending

Reported RD&D spending by IEA member governments on topics related to clean energy doubled between 2000 and 2010 to around USD 15 billion (IEA, 2016c), around 0.15% of their total budget expenses (Figure 2.3). This growth represents a fourfold increase if nuclear is excluded. However, spending on energy RD&D has stagnated since 2010, an observation that has underpinned the timely launch of the Mission Innovation initiative.[8] Countries that have signed up to the Mission Innovation pledge of doubling clean energy research spending over five years will seek to reverse this trend.

8. While the peak year since 2000 was 2009, this surge in spending was related to post-crisis stimulus packages targeted at large technology demonstration projects, such as the US American Recovery and Reinvestment Act of 2009.

Figure 2.3. IEA public energy RD&D budget by technology group



Notes: T&D = transmission and distribution. Basic energy research refers to basic research where the final application may not be attributable to a specific technology listed in previous sections. Included are the European Commission and state-owned enterprise expenditure where reported.

Key point *In real terms, public RD&D spending in IEA countries has bounced back since a low in 2000, with growth mostly in clean energy technologies.*

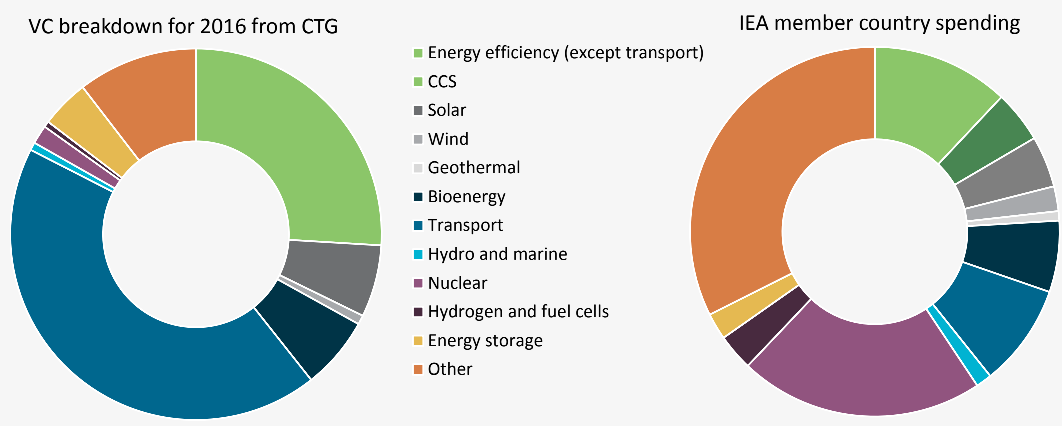
The share of RD&D spending that is not directed specifically to fossil fuels has risen from a low point of 80% in 1990 to 93% in 2015. Shares of renewables and efficiency each increased from just 7% of the total in 1985 to 20% in 2015, reaching almost USD 7 billion in 2015 when combined. Since 2010, budgets for fossil fuels (excluding CCS) have been constant in real terms at USD 1.1 billion.

The United States (35% of the total) and Japan (19%) are the countries with the largest absolute spending on energy RD&D among IEA members. Overall, energy RD&D is only around 4% of total R&D expenditure in IEA members, however. This level has more than halved since the 1980s, while defence research has remained dominant at around 30%.

IEA data demonstrate that public funding is striving to fulfil its prescribed function of supporting technologies that are further from the market or have high development and demonstration costs, including nuclear, CCS and ocean energy. This point can be seen in a comparison of the shares of public funding for different clean energy technologies and private funding by venture capital (Figure 2.4).

Data reported to the IEA indicate direct budget expenditures on RD&D, as well as R&D budgets of some state-owned enterprises. However, governments invest in clean energy RD&D using a more diverse variety of instruments and policies that can serve different purposes (Table 2.1). These instruments are most commonly employed at the level of national or subnational governments, but there is a positive trend toward more engagement of cities at one end of the scale and intergovernmental collaborations at the other. Cities can effectively support projects, such as smart city demonstrations, that are tailored to local needs, while international initiatives can fund projects that countries cannot fulfil alone.

Figure 2.4. Relative shares of clean energy technologies in public RD&D and venture capital (VC) funding



Source: Cleantech Group (2017), i3 database.

Key point *Governments tend to support a broader range of technologies than the private sector, showing the value of a portfolio approach to public RD&D funding.*

Table 2.1 Public instruments for supporting clean energy RD&D

Funding instrument or policy	Description	Purpose	Examples	Challenges
Tax incentives	Lower tax rates or rebates for R&D expenditures; tax allowances; payroll tax deductions; tax refunds for not-yet-profitable start-ups.	Encourage firms to undertake more RD&D in all sectors, raising skills and keeping local firms competitive.	Widely used across OECD countries.	Indiscriminately shared between research with and without a high social value. The risk of high budget costs means that available tax relief is sometimes capped. Can lead to competition between countries or regions for R&D talent, increasing costs. No mechanism for ensuring that the resulting research is of a high quality.
Targeted tax incentives	Favourable tax treatment for a specific sector or type of R&D.	Stimulate more activity in a part of the innovation chain or strategically shape a sector.	La jeune entreprise innovante (J.E.I.) in France. India tax exemption for start-ups involving innovation development START-UP NY.	

Public research labs	Government can employ researchers as civil servants and establish long-term research programmes.	Provides funding and job stability for researchers working on strategic topics free from commercial pressures.	US National Laboratories: National Renewable Energy Laboratory (NREL), Pacific Northwest National Laboratory (PNNL), Lawrence Berkeley National Laboratory (LBNL), ENL etc. Fraunhofer-Institut für System- und Innovation-forschung (Institute for Systems and Innovation Research) (Fraunhofer ISI). India Department of Biotechnology bioenergy research centres. King Abdullah Petroleum Studies and Research Center (KAPSARC). CanmetENERGY/ NRC (Canadian National Research Council).	Can entrench path dependency in research as expertise is difficult to shift to new topics. Budgets tend to be hard to vary significantly between funding cycles.
Research by state-owned enterprises	Governments can use their ownership rights to direct the level and type of research undertaken.	Support national champions that are committed to preserving the returns to RD&D within the country. Direct corporate strategy towards national interests.	Rosatom. Masdar. Vattenfall. State Grid Corporation of China (SGCC). Hydro-Quebec IREQ (Institut de recherche d'Hydro-Quebec).	Managerial incentives need to be aligned with ensuring the highest returns to innovation.
100% grants	Funding awarded to researchers in public or private institutions for projects selected by government agencies.	Address private underfunding of research and direct efforts towards government priorities.	China Key Technologies R&D Program.	Public funding of private research can risk "crowding out" private investment in RD&D.[9] Public funds may not be spent as carefully as a company's own resources.

9. While concerns have been raised about the possible "crowding out" of private sector RD&D investment by public RD&D expenditure, the evidence is mixed. In general, a large government initiative is considered to send a signal to private investors that outweighs the effects of competition for funding or human capital.

Co-funded grants	Funding for private research projects is contingent on use of own funds by the company, ranging from 5% to over 50% of costs.	Compared with 100% grants, co-funding reduces the risk of "crowding out" and uses public funds more efficiently.	Advanced Research Projects Agency-Energy (ARPA-E). Horizon 2020 Secure, Clean and Efficient Energy. Brazilian Development Bank Fundo Tecnológico (Technological Fund) (BNDES Funtec) Canada's Energy Innovation Program (EIP).	In most cases, the government funder does not retain any rights to the underlying intellectual property generated and benefits only indirectly from the returns.
VC and seed funding	Capital, usually equity, is provided to new, small enterprises in the expectation that they can be sold for a substantial profit several years later.	Government VC funds create a market for risky, commercially oriented innovation and can give a social direction to capital market-based technology selection.	Small Business Innovation Research (SBIR) in United States. Sitra in Finland. United Kingdom Innovation Investment Fund (UKIIF). Japan New Energy Venture Technology Innovation Project.	The short-term incentive structure of the VC manager, usually with a non-technical background, may be in conflict with broader social goals.
Prizes	Funding awarded to winners of competitions to meet a specific technology performance target or outperform rivals.	Use the prize money (or other reward) to stimulate innovation and help policy makers of technology status at reduced public cost.	Sunshot Prize. Horizon Prizes for PV, low-carbon hospitals and CO_2 reuse. EcoCAR.	
Loans and loan guarantees	Public loans can bridge funding gaps for companies on the verge of profitability, enabling them to construct demonstration plants or first-of-a-kind facilities.	Public lenders can be more tolerant of risk in the pursuit of public goods, lending at lower than market rates.	US loan (e.g. to Tesla). Loans to Renault and PSA Groupe for research into EVs (EUR 3bn).	Can be politically sensitive to failure and non-repayment. Only suitable for technologies that are already proven to be very close to market.

The portfolio of public RD&D investment can also include, for example, venture capital and seed funding, which are not solely the territory of private finance. Finland's Sitra directs investment to over 40 funds that support start-ups solving ecological, social and well-being challenges. While it is financed from the yield on its investments, its mission to help bridge the gap between R&D and deployment for clean technologies is enshrined in legislation.

The UKIIF has invested 150 million pounds (GBP) of public venture funds and GBP 180 million of private funds in different phases of innovation and prioritises clean energy. In the United States, SBIR provides seed funding to small innovative businesses, and a portion of its funding is awarded by the government's Office of Energy Efficiency & Renewable Energy. In many countries, governments are active in public-private partnerships, loan guarantees, incubators and business networks that facilitate early-stage investment in clean energy entrepreneurship.

The appropriate combination of policy instruments and funding sources differs for different technologies and industrial partners (Box 2.3). Direct support for RD&D (e.g. grants, loans, tax credits) and non-RD&D support for business innovation (e.g. support for venture capital and assistance for starting up entrepreneurial activities) need to be balanced with targeted policies that foster demand and markets for clean energy (e.g. pricing mechanisms, public procurement, minimum energy performance standards, energy efficiency labels and mandatory targets). Any of these policies implemented alone would be less effective and more expensive.

Box 2.3. Different types of technologies have different funding needs

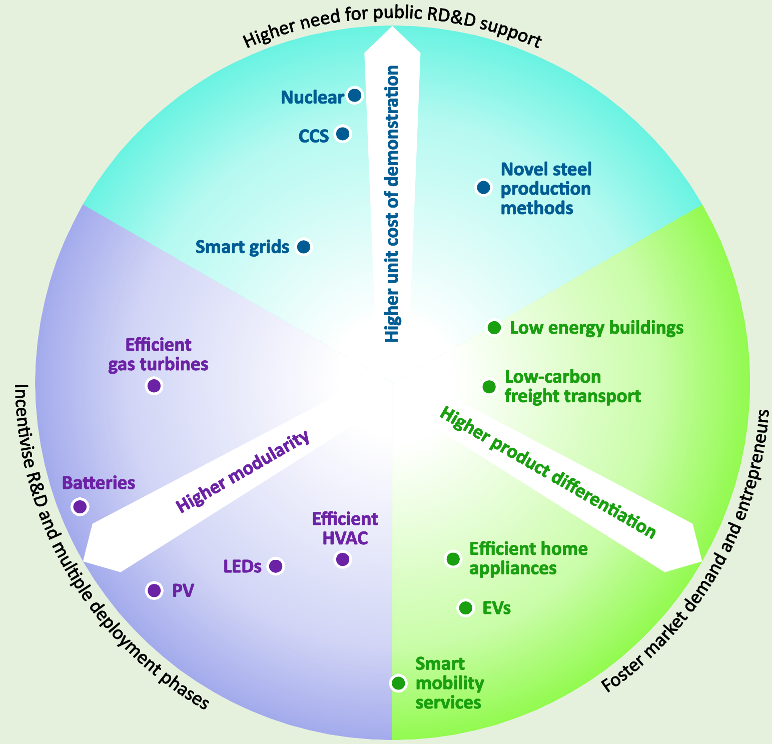
When the type of support and investment needed for RD&D are being considered, the characteristics of a technology are important. For example, empirical experience indicates that clean energy technologies with low unit costs of demonstration require a lower share of their RD&D funding from public sources (Figure 2.5). Conversely, technologies that have high modularity and ease of product differentiation are able to raise finance more easily if an initial market exists, even in the "high cost gap" stage.

In some situations, clean energy technologies share characteristics with the needs of other fast-evolving sectors and can piggyback on RD&D by a wider range of innovators, allowing investors from one sector to bear less of the total risk and financial burden. For example, a huge drive is currently under way to improve batteries for consumer electronics, transport and military purposes, and electricity storage for integrating renewables and shifting demand. These "spillovers" accelerate innovation in comparison with, say, new cement production methods.

Technologies with a high unit cost of demonstration require more capital to be put at risk in an early stage of the innovation chain. CCS, nuclear and integrated smart city solutions fall into this category due to their costs, situational specificity and value chain complexity. For nuclear innovation, the timescale of the development cycle is long due to the need to develop new qualification programmes and regulatory frameworks, which requires appropriate financial conditions. In the case of CCS, demonstration projects can cost around USD 1 billion, take five years or more from investment decision to gaining results, and currently have a market value of around one-tenth of their costs.[10] The regulatory changes that would make the demonstration risks attractive to the private sector alone are generally politically unpalatable, and governments accept a strategic role in a significant proportion of the costs, while providing signals that markets for these technologies will be supported in the future. In contrast, other technologies, such as software for energy demand management, have a very different risk profile at the prototype and demo stage.

10. Based on expected CO_2 prices for tradeable certificates or enhanced oil recovery (EOR) in the medium term.

2.5. Figure: Technology characteristics influence relative needs for public innovation support



Note: HVAC = heating, ventilation and air conditioning.

Key point: Different types of low-carbon technologies require different levels and kinds of public support.

Modular clean energy technologies that can be mass-produced include solar PV, LEDs, batteries, passenger vehicles and efficient appliances. In this way, substantial manufacturing experience can be generated for each doubling of industrial output. Such technologies can generally support a greater variety of competing manufacturers for a given production capacity and lend themselves to standardisation and more rapid cost reduction through learning-by-doing and scale economies. Private risk capital can be raised as for other commodity products, but may depend on commodity cycles. These characteristics give governments a role in early stage research; “market pull” policies, such as performance standards or consumer subsidies; and countercyclical support.

Some innovations allow different consumer segments to be offered differentiated products. For these technologies, governments can have a smaller role in creating initial “niche” markets for products. For example, high-performance EVs are affordable to wealthy early-adopter consumers to whom they provide status and pleasure. In the earliest stages of deployment, this differentiated consumer market partly reduces the total cost of subsidising purchases and can favour policies such as obligations on automakers to sell EVs.

Energy RD&D spending in the rest of the world

Data on energy RD&D investment by countries that do not yet report activity to the IEA are challenging to collect and track. They are generally not routinely collected or published but can in some cases be extracted from national budgets or financial reports of state-owned enterprises. For example, India publishes R&D spending in ministerial budgets.

By aggregating information from Mission Innovation submissions, national budgets and reports, we estimate clean energy RD&D expenditure by non-IEA member governments[11] to have been around USD 4.5 billion in 2015. This total includes spending by major state-owned enterprises in these countries, which is a dominant source of publicly directed clean energy RD&D in China. China alone represents three-quarters of the total, even though its total reported R&D spending by industrial energy enterprises using public funds and state-owned enterprises declined 11% since 2012 in real terms (China Statistics Press, 2016). The vast majority of this decline was related to coal, gas and oil companies and might be somewhat offset by an increase in clean energy R&D spending that is targeted by China, as it is in other Mission Innovation members. Unlike in IEA member countries, this report estimates that most public expenditure on energy RD&D in non-IEA member countries is directed to fossil fuel research, which is in accordance with the earlier result of Kempener et al. (2010).

Improvements on existing technologies are the main focus of current innovation efforts in emerging countries. That said, economic growth and capital accumulation have increased the exposure of economies in China, Southeast Asia, the Middle East and elsewhere to international technology through trade and foreign direct investment. Combined with investment in domestic skills development, this interaction with international technology and knowledge exchanges has contributed to emerging countries' growing capacity for a broader range of innovation effort. A particular opportunity exists for new, low-cost technologies that will be appropriate for these countries' specific circumstances and climates.

Most current collaborative activities in emerging economies focus on facilitating deployment rather than RD&D. Collaborative RD&D is often difficult, because sharing knowledge is risky, capabilities for innovation are limited in some countries, and national regulations and policies related to RD&D tend to differ. However, changes brought about by the globalisation of the economy and the pace of technology innovation have brought more co-operation in what is known as "open innovation" (IEA, 2015).

The IEA has a long history of facilitating international RD&D co-operation, and countries from around the world, including emerging and developing countries, are members of various IEA Technology Collaboration Programmes (TCPs). TCPs and other bilateral initiatives have encouraged joint calls for R&D and innovation projects using pooled resources from two or more governments. Joint calls are a valuable instrument for directing research towards appropriate technologies and building on knowledge in OECD and non-OECD countries.

Corporate energy RD&D spending

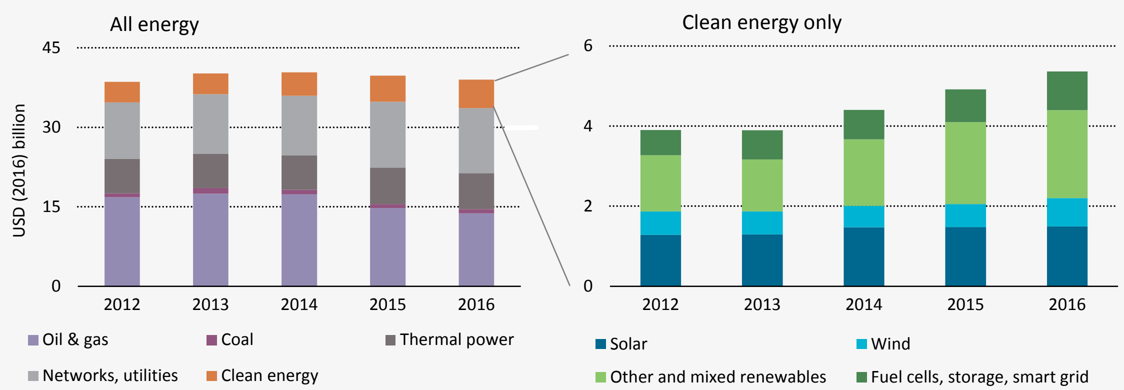
Existing data sources for corporate spending on energy RD&D, especially for efforts directed toward clean energy, are limited. This special feature lays out what is currently available and highlights key trends, all with an understanding that a significant opportunity exists for further improvement of data collection into the future to benefit decision making by government policy makers, companies, and other stakeholders. This knowledge gap is one that the IEA aims to work with business stakeholders to help fill.

11. Includes: Brazil, China, India, Indonesia, Mexico, Russia, Saudi Arabia, South Africa, United Arab Emirates.

Reported R&D spending by listed and other energy companies[12] worldwide declined by 2% per year in 2015 and again in 2016 (according to initial results), reversing a growth trend over the preceding years (Figure 2.6). However, much of this decline can be attributed to the drop in revenue of oil and gas companies rather than an industry-wide trend or an indication of lower R&D investment. While firms generally smooth their R&D spending over time, if possible, to retain key skills, this shows that R&D can be vulnerable to sharp changes in the total capital budgets of companies, especially in markets with volatile prices.

Figure

2.6. Reported R&D spending by energy companies according to sectoral classification



Notes: 2016 data are provisional, based on reporting by end April 2017. The reported data is in 2016 USD. Data from 2016 are estimates and are likely to be refined over the course of 2017. Classifications are based on BICS sectors and associated shares of revenue for all companies active in these sectors. This approach likely misallocates some clean energy R&D spending to thermal power OEMs and utilities. It omits companies domiciled in countries that do not require disclosure of R&D spending, but where clean energy R&D is likely lower.

Source: Bloomberg (2016). *Bloomberg Terminal*.

Key point *Clean energy spending remains a small but important – and growing – share of all corporate R&D spending.*

R&D expenditure by companies categorised as clean energy (or with reported revenue in clean energy categories) increased from USD 3.9 billion to USD 5.4 billion between 2012 and 2016. The share of clean energy in corporate energy R&D spending increased from 10% to 14% over this period, in large part due to the decline in oil and gas R&D expenditure.

Among energy companies, differences exist between sectors. Oil and gas companies and electric utilities, on average, both spend around 0.25% of their revenue on R&D each year, whereas thermal power OEMs and clean energy companies spend around 2.5% of their

12. Energy companies have been isolated according to BICS. Data limitations mean that energy efficiency R&D is underrepresented, because it is undertaken primarily by companies active in non-energy sectors, with attempts at fuller inclusivity have been made by allocating a percentage of such firms' R&D to energy topics according to the share of revenue from these activities. With the exception of firms assigned to alternative vehicle drivetrains and LEDs, R&D spending is extracted from the filed accounts of companies, for example, SEC 10-K filings in the United States. The cross-cutting nature of R&D activities by some companies means that some spending is not captured by this method.

revenue on R&D. This is reflective of the demands for innovation in the competitive markets for equipment and the less mature status of clean energy compared with oil and gas and coal mining.

Compared with sectors such as pharmaceuticals, consumer goods and automobile manufacturing, most energy company business models are not R&D-intensive. The number of energy firms in the top 1 400 R&D spenders has decreased since 2010, from 63 to 42 (EC, 2016). Automobile companies, whose in-house research makes up much of the world's work on efficient vehicle technologies, spend, on average, 3.2% of their sales revenue on R&D to stay competitive in a consumer-focused market. For some carmakers, such as Volkswagen, this percentage is as high as 7%. Revenue in this sector is large – if only half of that in oil and gas – so the absolute spending of all listed automobile companies was five times higher than that of oil and gas firms in 2015.

In 2015, members of the Breakthrough Energy Coalition[13] set the goal to raise their investments in clean energy R&D, including to make increased private sector investment that is more patient and risk-tolerant. Other industrial players have also recognised the need to accelerate clean energy R&D. Yet, while general trends may be discerned in corporate R&D spending, the available data are currently insufficient to reliably inform policy making.

The four main reasons a robust aggregation of private RD&D spending is currently not feasible using publicly available data are as follows:[14]

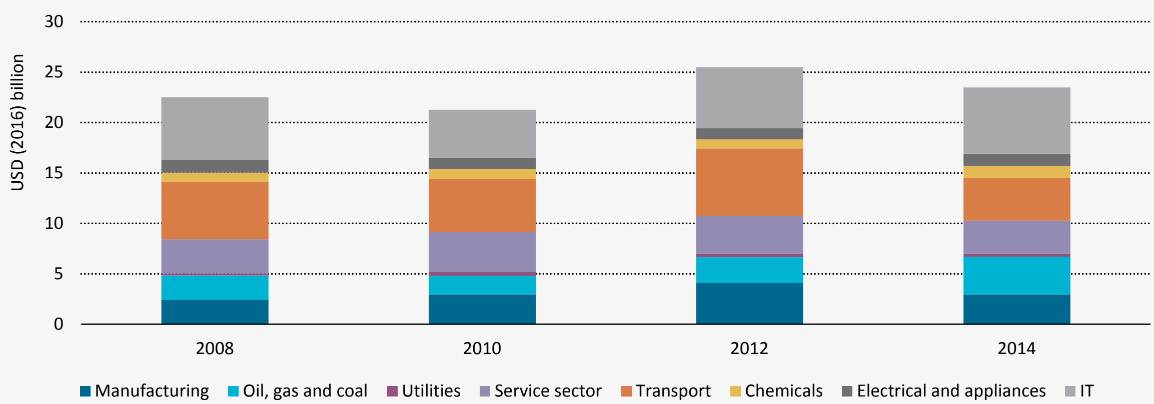
- Not all energy businesses submit annual financial reports that declare R&D spending; for example, start-ups and unlisted companies[15] do not publish such reports.
- Not all energy R&D spending is undertaken by energy businesses; for example, much of the research into energy efficiency is in the construction, manufacturing, automotive, information technology (IT) and consumer goods sectors.
- Companies that report R&D spending are often active in multiple sectors but report one corporate aggregate figure; for example, such companies include those that produce electricity-generating equipment and are also major players in health care development.
- Within the energy domain, corporate R&D spending is generally reported at a level that does not allow expenditure on different energy technologies to be disentangled. Definitions of what constitutes R&D expenditure can vary between companies and sectors, including whether or not the whole or incremental costs of an innovative demonstration project are reported.

Some governments overcome these challenges by undertaking surveys to learn about R&D spending in industry and include survey questions on energy, often within ongoing statistical business surveys. In the United States, for example, the Business R&D Survey has been carried out each year since 2008,[16] and companies are obliged to report their expenditure on energy technologies. The results show that the diversity of sectors that report energy R&D is much broader than traditional energy companies (Figure 2.7). In fact, most reported spending is by non-energy companies, proving the vital importance of looking beyond the energy sector for energy innovation. For comparison, the USD 23 billion reported in this survey is double the energy R&D spending by US companies that we have estimated based

13. The Breakthrough Energy Coalition is a partnership of large group of individuals and institutions committed to investing in new energy technologies emerging out of government research institutions to provide reliable, affordable power with zero emissions.
14. Each of these reasons indicates that our estimate of USD 5.4 billion for spending on clean energy R&D by private companies is an underestimation. In addition to not covering relevant R&D in certain companies or sectors, it is likely that some smart grids R&D is included within the "networks" category and some power generation efficiency R&D is included within the "thermal power" category.
15. Much of the research by large corporations is directed towards incremental and sustaining innovations that support the existing business interests of the firms. Smaller firms are more likely to pursue more novel, riskier technology options, partly because their prospects to enter the market depend on being able to differentiate themselves from incumbent companies.
16. As the successor of the Survey of Industrial R&D (SIRD), begun in 1953.

on financial reports and allocated according to revenue in all energy sectors in 2014 (described in the previous section) and almost four times the US public expenditure on all energy RD&D in that year.

Figure 2.7. Expenditures on energy R&D reported by sectors to the US Business R&D Survey



Source: NSF (2017), *Business R&D and Innovation Surveys 2008-2014*,

Key point *According to self-reporting by companies in the United States, most energy-related R&D is undertaken by companies outside the traditional energy sector.*

Italy's statistical service manages a survey that was adapted to the Energy Ministry's needs to distinguish between research into different energy technologies. The results are not published, but the aggregate reported total spending in 2014 was around USD 410 million, 59% of which was directed to energy efficiency and 19% to renewables.

Canada also surveys companies each year about their R&D spending on different energy technologies. Consolidated results are published through Statistics Canada, Canada's main statistics unit. These surveys demonstrate that governments can and do collect valuable data about private energy R&D spending trends, however, the questionnaire does not specify clean technology expenditures to be reported (Table 2.2). As with the US results, the Canadian survey shows industry energy R&D spending that is three times higher than Canada's government spending on energy R&D but the share of clean energy is only half (Statcan, 2017)

A third approach to estimating private sector R&D investment using a patent database is annually performed by the European Commission in the framework of the State of the Energy Union. A total of USD 17.4 billion was found to have been invested in clean energy research in the European Union in 2012 according to this method (EC, 2017). Building on the existing rigorous analysis for Europe, a speculative estimate for global annual private sector clean energy R&D spending is around USD 125 billion (Box 2.4).

Table 2.2 Examples of government surveys of industrial R&D energy expenditure

Survey	Legal basis	Number of energy technology categories	Threshold for inclusion	Number of companies	Year started	Latest year of data	Boundaries
Canada's Industry Energy Research and Development Expenditure survey	Responding to the survey is mandatory under the Statistics Act	7 main tech categories (plus 41 sub-categories)	Companies known or believed to be performing or funding energy R&D	2 350 (recipients of the survey)	Prior to 2000	2014	Includes intramural expenditures and extramural payments outside Canada
Italy National Institute for Statistics (Istat) survey	Istat annual compulsory survey	20	–	1 000	2007	2014	Follows IEA definitions
US Business R&D Survey	Compulsory under Title 13, US Code	1	Companies with known R&D activities	45 000 (results extrapolated to a population of 2 million companies)	2008 (in its current form)	2014	Routine product testing and prospecting for natural resources not included

Box 2.4. Measuring corporate R&D spending via patent statistics

The Joint Research Centre of the European Commission undertakes detailed annual analyses of reported corporate R&D spending and published patents for different clean energy technologies (grouping renewable energy technologies, smart energy systems, efficient energy systems, sustainable transport, carbon capture utilisation and storage, and nuclear safety). The combination of these datasets, coupled with more detailed information about the values of different energy technologies in companies' overall business activity and other factors, enables the calculation of average research costs per patent per technology per year (EC, 2017). Multiplied by the numbers of patents, the resulting estimate of total investment in clean energy R&D in the European Union in 2012 is USD 17.4 billion.

The method provides the most comprehensive estimate available for Europe, but has some drawbacks for tracking purposes. For example, patent statistics are published with a time lag, meaning that the most recent complete dataset at the time of writing refers to 2012. Constructing and maintaining a quality, coherent and consistent dataset is a labour-intensive exercise. Also, the method assumes that the patenting strategies of companies that report annual R&D spending are the same as those that do not, and that these strategies do not change over time.

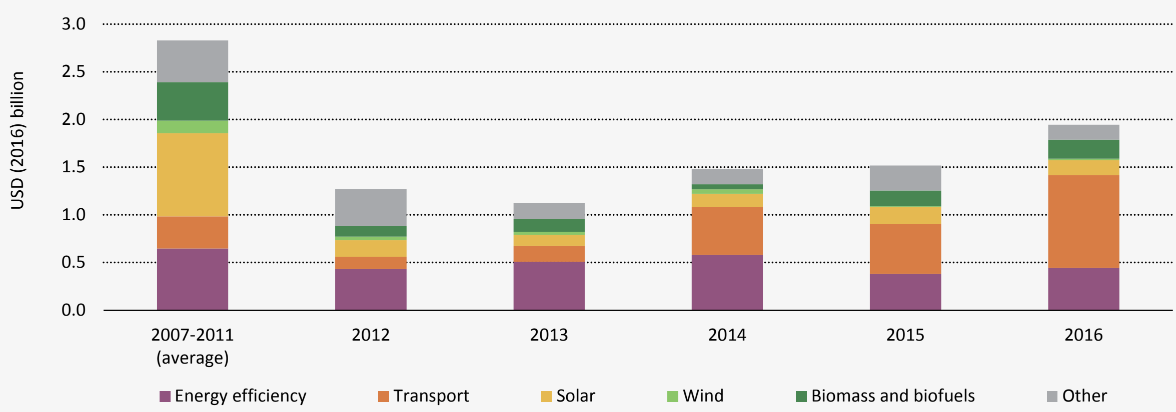
The source of financing used by a company for R&D can affect its cost. Many large corporations fund R&D activities from their balance sheets, giving them a relatively low cost of capital compared with smaller companies that are more reliant on bank lending. As bank lending tends to be more risk-averse, a high share of third-party financing can be associated with less radical and more incremental innovation, especially during macroeconomic uncertainty (Nanda and Nicholas, 2014).

Over the past decade, the amount of bank financing for corporate research by larger companies has increased, in some cases because it is a cheaper source of capital than retained earnings, with around 40% of firms registering patents in the US having pledged patents as collateral for debt (Mann, 2016). This is an area where public policy may have a role to play in ensuring that financing costs are aligned with long-term objectives.

Venture capital (VC) funding of energy innovation

The early commercial development of a new clean energy technology is increasingly undertaken by a start-up company with VC funding. In 2016, VC funds invested around USD 2 billion in early stage clean energy firms, one quarter of the level of reported corporate spending on clean energy R&D (Figure 2.8). However, clean energy makes up a small fraction of total VC funding. In 2016, it was just 3% (KPMG, 2017).

Figure 2.8. Early-stage VC investment in clean energy topics



Note: The reported data is in 2016 USD. Early stage includes seed, series A and series B rounds. Other includes energy storage, fuel cells, geothermal, hydro, marine, nuclear, smart grids.

Source: Cleantech Group (2017).

Key point *Early-stage VC funding for clean energy has grown at 20% per year since 2013, but the technology mix has become more "capital light".*

VC targets early-stage firms that are aiming to take an idea to the market, usually after basic research and testing in public or industrial research labs. Often, VC investors follow "angel investors", who have a higher risk appetite and will take a significant equity stake in the first round of seed funding for a novel idea – between USD 100 000 and USD 1 million.

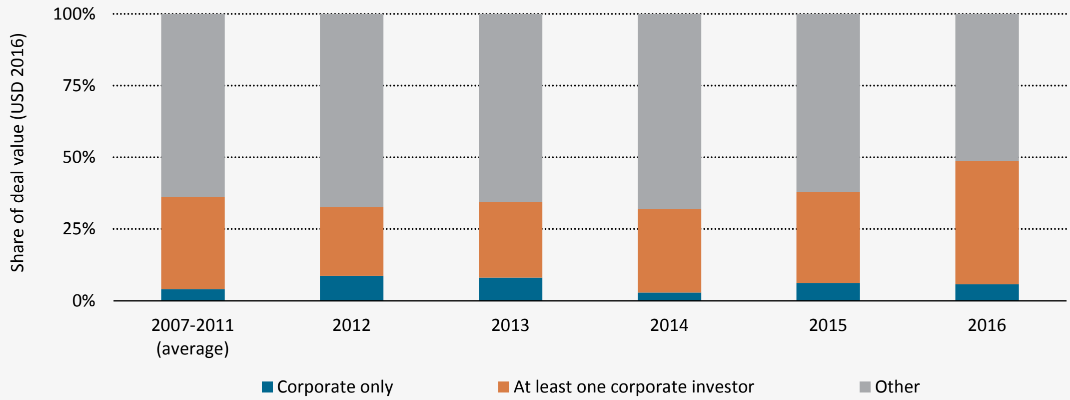
Both angel and VC investors seek to sell their shares for large profits within a time frame of around five to seven years.[17] Compared with bank finance, VC monitoring improves governance for small businesses and can increase the rate of radical innovation due to a tolerance of failure in the expectation of a few major successes.

While governments signal the importance of clean energy innovation and in some cases specifically support VC activity, the two are often not well matched. The time frame to learn about the viability of energy projects can be too long, the capital requirements for technology demonstration too high, and the consumer value too low. Such technologies may get attention when financial markets are hot, but not when they are more risk-averse. In 2012, the first wave of cleantech VC crashed as investors learned that the VC model was ill-suited to asset-intensive RD&D, such as solar and bioenergy.

The role of VC in the energy sector has been reinvigorated since 2013 but is not yet at pre-2012 levels. This has been led by the rise of digital technologies in all parts of the value chain, in particular in consumer-facing segments. Technologies such as cloud computing, computer simulation, rapid prototyping and object-oriented programming have lowered the costs of learning about viability in a technology's early stages. Excluding mobility services, clean transport technologies accounted for over half of all clean energy VC activity in 2016, reflecting the growth of software and automation start-ups for driving applications. This has changed the technology mix of clean energy VC activity.

Another factor in rising clean energy VC activity is an increase in corporate VC involvement (Figure 2.9). By nurturing promising start-ups outside the confines of company management and payrolls, venture investing can increase the flexibility and option value of corporate innovation. Corporate VC funding appears set to increase further for clean energy. However, unless that capital is successfully directed to innovations in infrastructure and hardware as well as software, the need for government funding and corporate labs in the energy transition will not diminish.

Figure 2.9. Corporate involvement in early-stage VC transactions



Note: Early stage includes seed, series A and series B rounds.

Source: Cleantech Group (2017). i3 database.

Key point *Since 2014, corporate involvement in early-stage clean energy VC has grown from one-third to almost half of all transactions, reflecting a shift in corporate RD&D strategies.*

17. While venture-funded start-ups can be innovative, Bernstein (2015) found that the level of innovation spending tends to fall after successful public offerings of start-ups on a securities exchange.

Recommendations

Assessing current levels of energy RD&D investment is not straightforward, and further improvements are advisable and possible. Furthermore, no perfect formula exists for how governments should spend their RD&D budgets.[18] With that said, the following recommendations can assist countries, companies and stakeholders to better take advantage of clean energy innovation opportunities.

Collect better data on public and private RD&D investment

- Better understanding of the status and breakdown of public and private investments for RD&D will enable policy makers to better identify gaps and to enhance efficiency of public finance allocation. Sufficient detail about how budgets are allocated to different technology areas is required, i.e. at the level of the specific type of solar cell rather than PV in general. All the public investments in RD&D should be captured separately, including grants, tax breaks, state-owned enterprise spending, and loans or equity for start-ups. The IEA survey for RD&D spending by its member countries provides a robust and tested methodology for collecting and reporting data at a variety of different technology levels and, importantly, provides like-for-like comparability.
- Governments should consider using surveys to collect better data on private sector energy R&D spending. Such data collection should use technology categories that are consistent with those used for reporting public spending data and that capture vital energy efficiency technology progress outside traditional energy sector companies. The national surveys of private sector energy R&D activity established by Canada, Italy and the United States provide examples of good practice but also show opportunities for greater harmonisation, notably through increased commonality between public and private sector reporting.
- The IEA would be interested in further enhancing its capabilities to serve as a central hub of energy R&D data from both governments – including current IEA members, partners, and other key countries – and the private sector.

Develop and track key performance indicators for priority technologies

- Measurement of progress in clean energy innovation needs to go beyond the flow of money and should aim to ask a set of core questions about individual technologies.[19] Accelerating energy transitions depend on the outcomes of the funded innovation programmes. Up-to-date information on performance and economic characteristics for energy technologies is needed to inform and adjust strategies for innovation prioritisation and market support.

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18. Indeed, few methods are available for assessing the impacts of RD&D spending; the timing of results can be hard to predict, and projects can generate valuable spillover effects in other technologies or sectors that are hard to quantify (Jaffe, 2002). For example, among the objectives of the European Commission's Horizon 2020 research and innovation programme are economic growth, job creation, researcher mobility and supporting the external policies of the European Union.
19. The following questions of individual technologies are of high relevance: How is performance improving at the cutting edge of the technology, and how is it measured? What are the relative costs and benefits of commercially available versions of the technology? How smooth and rapid is the journey from lab to market for this type of technology? Are research priorities easily adjusted according to new information? Do the sources of finance match the technologies' RDD&D needs? Are the most appropriate versions of the technology being developed for the regions of the world where they will be most needed over the 2DS time frame?

- Performance indicators should be internationally comparable and available at the highest level of detail that avoids compromising competitive advantage. In many cases, defining these indicators will require the development of impartial and broadly agreed standards for defining and testing the performance of low-carbon technologies. Performance and cost metrics could be complemented by target-setting exercises, such as the development of Technology Roadmaps that establish milestones and responsibilities.[20] Performance indicators need to take into account the cost and performance needs of low-income level consumers, where significant potential for achieving the 2DS has been identified.
- As an example, the European Commission's Strategic Energy Technologies Information System (SETIS) was established to monitor the development of innovative energy technologies and system solutions. A mechanism is currently being established that will assign a set of Key Performance Indicators (KPIs) for priority technology areas (EC, 2016). Performance will be reported annually against these KPIs, which include current and future market penetration, techno-economic performance, and prices.

Increase the level of collaboration and exchange on innovation policy

- A wide variety of models of innovation collaboration exist around the world, among both governments and public-private partnerships. Governments and companies currently work together on projects that range from sharing information on technology deployment (e.g. EVs, PV and heat pumps) to undertaking joint research into technologies of common interest (e.g. IEA TCPs, US-China Clean Energy Collaboration).
- Best practice in alignment and facilitation of different stages of innovation is not widely disseminated. Greater international exchange of knowledge is needed on how to identify priority technologies, how to match the sources of R&D financing with innovation needs and how to assess R&D outcomes.[21]
- Several frameworks for intergovernmental collaboration on clean energy could be leveraged for this purpose. Mission Innovation (Box 2.5) and the IEA Technology Network are pertinent examples.

20. For nearly a decade, IEA *Technology Roadmaps* have helped set the global agenda for clean energy technology development and deployment. The programme has been a considerable success and has provided recognised guidance to the public and private sectors, in part due to its collaborative nature, authoritative guidance on the priorities and steps needed to accelerate technology innovation and deployment, and emphasis on broad stakeholder engagement and consensus. The roadmaps each contain recommended actions, including RD&D priorities and targets, showing policy makers, investors and entrepreneurs, who are navigating an increasingly diverse and regionally specific energy landscape, how they can jointly act to transform the global energy system.
21. Priority action should close research gaps and avoid duplication of effort worldwide. There is value in sharing experiences with how to allocate resources between necessary incremental improvements and radical technologies that could dramatically reduce the reliance on known but highly uncertain solutions. In addition, cross-fertilisation with basic research advances in other fields, such as advanced materials and biotechnology, is dependent on innovation policy strategy.

Box 2.5. Mission Innovation: An innovation initiative for accelerating the energy transition

Mission Innovation is a landmark intergovernmental initiative launched in December 2015. It groups together 22 countries and the European Commission to mobilise support for clean energy technologies, in part through doubling clean energy R&D over five years.

Seven Innovation Challenges have been launched with the aim of catalysing global research efforts to meet Mission Innovation goals of reducing GHG emissions, increasing energy security and creating new opportunities for clean economic growth:

- Smart Grids
- Off-Grid Access to Electricity
- Carbon Capture
- Sustainable Biofuels
- Converting Sunlight
- Clean Energy Materials
- Affordable Heating and Cooling of Buildings.

Work programmes for the Innovation Challenges are in preparation in the first half of 2017. Increased engagement from the global research community, industry and investors is being encouraged, alongside collaborations between Mission Innovation members on these topics. Participants undertake working closely with private sector leaders, including through collaboration with the Breakthrough Energy Coalition – a partnership of 28 investors from ten countries committed to investing in new energy technologies that emerge from government-funded research in Mission Innovation countries.

The countries that make up Mission Innovation have reported approximately USD 15 billion per year of total investment in clean energy R&D today. Because Mission Innovation is a voluntary initiative, the methodologies behind countries' investment estimates are not formally co-ordinated, and countries can choose what technologies they include as "clean" energy. For example, only 9 of the 22 countries include nuclear energy, while 12 include cleaner fossil energy. Renewables and energy storage are the only technology areas included by all countries.

Enhance regular tracking of innovation progress by public and private sectors

- While deployment of clean energy technology is increasingly well disseminated, information sharing about technology progress at the innovation frontier is lagging behind. This failure is due to the paucity of available data and legitimate confidentiality concerns.
- Communication of progress in technology innovation can not only stimulate further discussion among experts, but can also unlock additional investment opportunities. One effective mechanism for communicating progress is to regularly highlight breakthroughs that have resulted through research programmes and create a buzz about what the novel technology, or combination of technologies, might deliver in terms of costs and benefits if momentum is maintained.

- The tables that follow this special feature provide an overview of how progress could be reported for key technologies identified in *TCEP 2017*.

Conduct clean energy RD&D investment in concert with the other key elements of the innovation ecosystem

- Effective RD&D investment is one element in a coherent system of innovation that includes early-stage niche markets, often supported by policies, and the broader competitive landscape. Effective priority setting and investment should take account of short-term and long-term perspectives and all relevant levels of activity: international, national, municipal, company and entrepreneur. In the international environment, initiatives such as Mission Innovation can benefit from linkages with the Breakthrough Energy Coalition and the Clean Energy Ministerial to cover the value chain from research to venture funding and deployment.
- Misalignments in the wider innovation system present barriers to effective RD&D and deployment.[22] Countries can and should explore whether different elements of their innovation ecosystems are working harmoniously and in accord with their national strengths and opportunities.
- A government's overall policy package should support knowledge development, feedback processes, entrepreneurship, market formation, education, industrial support and mitigation of resistance to change at all stages of the innovation pathway. It should allow experimentation in many small units and be tolerant of failures and disruption in order to achieve long-term success.[23] Factors such as visibility of future energy market regulation and rewards for longevity, instead of short-termism, are important to encourage private sector innovation in clean energy

22. For example, RD&D investments in energy efficiency are sometimes made alongside subsidies to retail consumers of fossil fuels, or RD&D investments in wind energy are encouraged despite local planning laws that prohibit the installation of wind turbines.
23. Governments can take a portfolio approach to supporting technologies that have high potential but low certainty, as well as those with high chances of success but lower performance. A portfolio approach recognises that not all ventures and projects will succeed, just as venture capitalists anticipate a success rate of under 40% but target a small number of highly beneficial breakthroughs.

Table 2.3 Tracking technology R&D challenges to achieve the sustainable energy transition

		Key RD&D challenges	How critical is it to the 2DS?	Why is this RD&D challenge critical?	Key RD&D focus areas over the next 5 years
Power generation	Solar PV	■ Reducing balance-of-system costs		■ Non-PV panel cost reductions needed to reduce system costs (Si-based panels now constitute less than 30% of the system cost)	■ Development of high efficiency conversion materials to reduce balance-of-systems costs
		■ Reducing plant-level integration costs		■ Plants will have to increasingly contribute to their own integration costs with solar PV penetration increase	■ Reduce costs and increase functionality of inverters; develop interoperable digital and electrical interfaces; remote digital monitoring and maintenance;
		■ Increasing efficiencies beyond 24% PERC		■ Having crossed the 1 USD/W threshold for module manufacturing, high conversion efficiencies will be the largest contributor to future PV cost reductions	■ Develop new materials for PV panels (e.g. alternative technologies beyond c-Si)
	Wind Power	■ Improve resource assessment and spatial planning		■ Wind farm planning, both onshore and offshore, will require enhanced sensitivity assessment of the surrounding environment to ensure long term turbine efficiency and attractive return on investment	■ Improve the accuracy of offshore pre-construction planning to accommodate seasonal and yearly variations changes in the wind resource; refinement and validation of model outputs against measured data;
		■ Reducing plant-level integration costs and		■ Wind farms need to ensure their value to the system is maintained with the high penetration levels in the 2DS	■ Enhance short-term forecasts to facilitate the integration of higher volumes. Innovate big-data analytics from plant-level measurements
	Hydropower	■ Improved spatial planning and environmental assessments		■ Hydropower sees a two-fold growth in the 2DS, but its potential is highly constrained by geography and robust planning	■ Designing, testing, and validating new ways to improve sustainability and reduce the environmental effects of hydropower generation on fish populations and ecosystems
		■ Enhance flexibility of hydropower		■ In the 2DS, hydropower will be increasingly called upon to provide flexibility to accommodate changes in both supply and demand	■ Quantify the value of services that support the resilience of the electric grid
	Gas-fired power	■ Flexible operation of gas power plants		■ Existing gas power capacity is not optimised for the flexibility requirements of systems with higher shares of variable renewables	■ Explore technical options for retrofitting gas fired power plants and assess their economics against other flexibility options
		■ Use of next generation fuel cells (e.g. hydrogen)		■ Fuel cells produced from excess power during periods of abundant renewables generation could play a key role in power systems	■ Increase activity and utilisation, or fully avoid the use of platinum; direct R&D to increase durability and reduce degradation of fuel cell mechanisms
		■ Cost-competitive hydrogen turbines		■ Potential for hydrogen use at a larger scale, including injection of power in the electricity grid from long-term hydrogen storage	■ Explore technologies that provide enhanced material capabilities, reduced air cooling and leakage, and higher pressure ratios than conventional turbines
	Coal-fired power	■ Increasing combustion temperature and efficiencies		■ High efficiency low emissions coal power is a requirement for new coal power plants	■ Explore technical options for retrofitting coal fired power plants and assess their economics against other flexibility options
		■ Operation under low load		■ Coal power suffers an efficiency penalty when ramping frequently, which is exacerbated with the power mixes in the 2DS	
	Nuclear power	■ Cost-effective life extensions beyond 50-60 years		■ Required rates for nuclear plant construction could be reduced by life extensions of existing plants	■ Explore new materials and retrofitting technologies for life extensions
		■ Small-scale, modular reactors		■ Small modular reactors open up possibilities for small scale nuclear power in new countries and niche markets	■ Develop improved materials and fuels for advanced SMR designs; direct R&D towards manufacturing processes to compete with economies of scale in large-scale reactors
		■ Nuclear combined heat-and-power		■ Nuclear energy is also a low-carbon source for heat and can play a relevant role in decarbonising other parts of the energy system	■ Explore extraction technologies and processes for district heating of buildings, seawater desalination, industrial production processes and fuel synthesis

		Key RD&D challenges	How critical is it to the 2DS?	Why is this RD&D challenge critical?	Key RD&D focus areas over the next 5 years
Industry	Chemicals and Petro-chemicals	Naphtha catalytic cracking		This technology shows energy savings compared with the widely used steam cracking process	Explore avenues for further commercial deployment and increasing throughput
		Use of biomass-based feedstocks		CO_2 emissions associated with feedstocks for chemical production can be avoided using biomass to produce light olefins, methanol and ammonia	Promote further research to reduce energy consumption and costs in current biomass-based chemical production
		Electricity-based hydrogen for ammonia & methanol		Ammonia and methanol production through renewable electricity-based processes removes all direct carbon emissions.	Further research to bring down costs and increase capacity of electrolysers
	Pulp & Paper	Black liquor gasification		Gasification of black liquor could increase the flexibility of end-uses for biomass-based by-products from the pulping process.	Scale up development of gasification designs, including low-temperature steam reforming process and high-temperature entrained flow reactor
		Lignin extraction		Lignin can be isolated as a potential feedstock for new industrial products, such as new chemicals and plastics	Develop lignin extraction processes that fulfill technical and economic maturity market requirements
		Low carbon alternatives to traditional pulping		Alternative processes using deep eutectic solvents could have significantly lower carbon footprints for pulping, and could produce additional added value for pulp producers through the sale of pure lignin as a material	Conduct first feasibility studies and pilot testing of this process will bring it closer to commercialization
		Alternative drying and forming processes		Alternative drying and forming processes with lower water content could reduce energy consumption in these two steps	Conduct additional study and testing is needed to bring these alternative processes to the market
	Iron & Steel	Coke oven gas (COG) reforming		COG reforming partially converts carbon compounds into hydrogen and carbon monoxide. Through integration with oxy blast furnaces, coke consumption is considerable reduced for pig iron production and it enables CO_2 capture	Develop commercial scale demonstrations
		Blast furnaces with top gas recovery		Top gas reuse in oxy blast furnaces reduces coke use in pig iron making, and can enable easier carbon capture.	Develop commercial scale demonstrations
		Upgraded smelting reduction (SR) and DRI		Enhanced SR and DRI processes have reduced energy intensity compared to their standard commercial process, respectively, and facilitate CO_2 capture through oxygen operation.	Develop commercial scale demonstrations for upgraded SR and promote long-trial pilot plant testing for upgraded DRI
		Electrolysis for iron making		The wider sustainability benefits of electrolysis processes rely on the use of renewable-based or carbon-free electricity.	Pilot projects are needed since the concepts have been proven only at experimental scale.
		Electricity-based hydrogen as reducing agent		Use of electrolysis-based hydrogen based on renewable electricity in iron production would displace fossil-based reducing agents	Demonstration projects are needed to integrate this technology in iron making processes
	Aluminium	Enhanced use of inert anodes		Carbon anodes produce CO_2 as they degrade; inert anodes would produce pure oxygen, greatly reducing process CO_2 emissions	Explore use of alternative materials to replace carbon-based anodes
		Direct carbothermic reduction of alumina		Direct carbothermic reduction of alumina could reduce energy consumption by 20% but has substantially lower aluminium conversion yields than standard processes.	Research ways of enhancing aluminium conversion yield issues to scale up this technology
		Kaolinite reduction		Kaolinite reduction could reduce on-site energy requirements by 15% and use lower quality bauxite	Demonstrate commercial kaolinite reduction and reduce material requirements of the process
	Cement	Oxy-combustion		Use of oxygen-enriched gas in the combustion process can increase the concentration of CO_2 in the flue gases and enable CO_2 capture	Oxy-combustion both for the pre-calciner and the kiln should be demonstrated at large scale
		Alternative clinkers and cement products		Alternatives to traditional clinker and Portland cement could reduce CO_2 emissions associated with calcination	Further testing of new products is needed to be accepted within regulatory frameworks and to develop experience in their use by end users

		Key RD&D challenges	How critical is it to the 2DS?	Why is this RD&D challenge critical?	Key RD&D focus areas over the next 5 years
Transport	Electric Vehicles	Reducing costs and increasing energy density of batteries		Batteries are the most expensive component of EVs, improving their energy density allows for weight reductions and range extensions, increasing the value proposition of EVs to consumers	Develop of novel battery chemistries and scale up their mass production
		Improving zero emission vehicle infrastructure		The availability of charging infrastructure is correlated with EV uptake	Improve infrastructure development through scaled up deployment and best practice business models for self-sustaining market conditions
		Integration of electric vehicles in the electricity grid		The limited capacity of the existing grid infrastructure can be one of the first bottlenecks for widespread EV uptake	Research and develop standards and regulations enabling widespread use of demand side management practices
	International Shipping	Increasing ship efficiency and integrating wind assistance		Limitations to the widespread uptake of cost effective energy efficient technologies in shipping	Enhance development of fuel saving technologies through learning by doing by deployment of retrofits and improved wind assistance.
		Demonstrating zero emission technologies for shipping		Decarbonising long distance transport modes will require zero emission technologies	Develop the technical feasibility and cost prospects for zero emission technologies (e.g. electrification and hydrogen) in different applications
		Demonstrating the use of low carbon fuels in shipping		Decarbonizing shipping will require the use of low carbon fuels	Transform the experience with the use of low carbon fuels into the shipping sector, develop technical specifications of low carbon fuels
	Fuel economy of LDVs	Technologies reducing vehicle weight, improving rolling resistance and aerodynamics		Technologies allowing energy demand reduction at the shaft enable a wide range of cost reductions and favour the deployment of other energy saving technologies	Deploy adequate policy tools that give a signal to R&D actors on what activities could best complement market deployment.
		Technologies improving the efficiency of ICEs, hybrids		Energy efficient ICEs and hybrids provide the bulk of the short term emission reductions from powertrains used on PLDVs and trucks	Set clear and transparent regulations (e.g.fuel economy regulations and differentiated taxation on vehicle purchase) to drive R&D that maximises the existing cost-efficient potential
	Transport Biofuels	Increased production of advanced biofuels from sustainable waste and residue feedstocks.		Low carbon fuels have a major importance for the decarbonisation of long distance transport modes. Advanced biofuels are one of the key options available for use in this sector.	Production scale up at commissioned commercial scale cellulosic ethanol plants through debottlenecking, to pave the way for lower-cost replication facilities. Ongoing technical research to widen waste and residue feedstock base for HVO production.
		Hydrogen and synthetic fuels from low carbon sources		Synthetic low carbon fuels are one of the options that could ensure decarbonisation of long distance transport modes	Advance sustainable and cost effective production of hydrogen and synthetic fuels from renewable electricity/biomass resources and improve their thermodynamic efficiency
	Aviation	Developing energy efficient technologies		Technologies allowing to reduce the energy demand of aircraft account for most of the energy savings from aviation in the short term	Develop energy efficient technologies (e.g. lightweight materials and advanced engine concepts)
		Demonstrating the commercial feasibility of innovative aircraft configurations		Long term energy efficiency improvements require major aircraft technology development, including changes in the conventional aircraft configuration	Demonstrate the commercial feasibility of innovative aircraft configurations, such as hybrid wing body aircraft architectures
		Improving air traffic management technologies		Improved air traffic management can deliver significant fuel savings thanks to the minimisation of flight distances	Demonstrate air traffic management (ATM) technologies enabling optimised routing and the minimisation of flight distances
	Trucks/ Heavy duty vehicles	Material substitution, low rolling resistance tyres, improved aerodynamics, more efficient powertrains		Technologies allowing to reduce the energy demand of trucks and powertrains currently widely deployed account for most of the energy savings in the next few years	Deploy adequate policy tools and transparent regulation that gives a signal to R&D actors on what priority areas could best increase efficiency in the short-term
		Demonstrating electric road systems for road freight		Decarbonising long distance transport modes will require zero emission technologies	Demonstrate Electric Road Systems and identify optimal option between conductive and inductive technologies for scale up.
		Demonstrate and deploy zero emission infrastructure based on hydrogen		Decarbonising long distance transport modes will require zero emission technologies	Identify the best solution allowing the deployment of hydrogen distribution infrastructure, taking into account for the cost of electricity and the costs of centralised production and hydrogen distribution infrastructure

		Key RD&D challenges	How critical is it to the 2DS?	Why is this RD&D challenge critical?	Key RD&D focus areas over the next 5 years
Buildings	Building envelopes	Achieve high levels of near-zero energy building construction at lower costs		Near-zero energy building construction will play a major role in addressing long-term energy demand for heating, cooling and lighting in buildings	Delivering affordable near-zero energy building construction and promoting very high-performance building envelope components
		Demonstrate and deploy affordable deep energy renovations for existing buildings		Deep energy renovations (e.g. 30% to 50% energy intensity improvement or greater) will be critical to improving energy demand in existing buildings	Establishing policies and market incentives to scale up deep energy renovations and lower costs
		Develop advanced building materials and integrated envelope solutions		Advanced building materials and high-performance integrated envelope solutions, both at affordable costs, are key to ensuring achievement of deep energy renovations and near-zero energy building construction	Supporting development and demonstration of highly insulated and integrated building envelope solutions at negative life-cycle cost
	Lighting, appliances and equipment	Improve thermal distribution and control systems		Optimisation of heating and cooling energy demand through improved controls offers considerable potential to save large quantities of energy.	Deploying improved controls (e.g. smart thermostats) across all buildings; Development of dynamic, connected energy management systems
		Solid state lighting at lower costs, higher performance and greater reliability		Despite efforts to phase-out incandescent lighting, major energy efficiency gains can still be achieved from high-performance lighting solutions	Setting minimum lighting energy performance criteria and working with manufacturers to ensure product reliability and improve lighting efficacy
		Demonstrate/deploy high-efficiency appliances with demand response		Responsive and energy-efficient technologies are key to addressing rapidly growing electrical plug loads and appliance ownership in buildings	Deploying high-efficiency appliance technologies for major appliances and setting energy performance standards for networked devices
		Increase uptake of high-performance heat pump technologies for multiple applications and climates		High-performance heat pump technologies can drastically reduce energy demand across multiple applications, including space heating, water heating, space cooling and major appliances	Developing and deploying high-performance heat pump solutions, including better responsiveness to demand (e.g. temperature change response), better control of latent heat, and improved performance in harsh climates
Energy Integration	Renewable Heat	Demonstrate flexible and integrated district energy solutions, including low temperature heat		Advanced district energy systems can take advantage of multiple energy opportunities across an integrated energy network, notably by providing enhanced flexibility to the energy system as a whole	Advancing low-temperature distribution for district energy networks and bringing forward cost-effective and integrated district energy solutions (e.g. building envelope measures with high-performance district energy)
		Reduce costs and increase uptake of solar thermal heat solutions		Solar thermal technology, including integrate district energy solutions, will play a major role in reducing fossil fuel consumption for heat demand	Achieving greater market scales and reducing costs for solar thermal installation and maintenance
	Carbon Capture and Storage	Reduce the capital cost of CO_2 separation and lower the energy penalty		CCS construction costs will be important regardless of future fuel prices. Current commercial capture technologies have limited room for significant efficiency improvement, which demands novel approaches	Optimise engineering solutions and prove effectiveness of membranes, adsorbents, ionic liquids, fuel cells, enzymes, chemical looping and new power cycles at larger scales
		De-risk and develop a wide portfolio of CO_2 storage resources including alternative storage options		Research and development of sufficient storage capacity in various settings in all relevant world regions is critical for enabling cost-effective CCS deployment	Optimise injection development plans and operations in saline aquifer injection and develop and demonstrate CO_2 storage potential in alternative storage settings such as basalts, ultramafic rocks, or via other mineralisation routes
	Energy storage	Long-term storage durations		With higher penetrations of renewable energy, systems could see extended periods with low generation from wind and solar	Flow batteries are highly promising but long-term performance and reliability issues as the technology scales up need addressing
		Reducing battery integration costs		While battery cell costs have greatly dropped, the cost of integrating them within systems can be as high as 60% of total costs in some markets	Develop standards and interoperability requirements that are tailored to local needs to spur decentralised innovation
		Advanced battery recycling		With higher numbers of Evs on the road and consumer electronics, components could be recycled to avoid supply crunches and large amounts of batteries could be re-purposed for power applications	Expand R&D on re-usability and re-cyclability along battery supply chains that is aligned with the envisaged technology and chemistry deployment pathway

Note: This table aims to complement the *TCEP 2017* and provide an overview of how progress in RD&D challenges could be reported for key identified technologies. The list of technologies is non-exhaustive.

Annexes

Acronyms, abbreviations, units of measure and regional groupings

Acronyms and abbreviations

2DS	2°C Scenario
ASEAN	Association of Southeast Asian Nations
BATs	best available technologies
BEV	battery-electric vehicle
BICS	Bloomberg Industry Classification System
BTX	benzene, toluene and xylenes
CCS	carbon capture and storage
CEPI	Confederation of European Paper Industries
CNRC	Canadian National Research Council
CO_2	carbon dioxide (CO_2)
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CSP	concentrated solar power
DRI	direct-reduced iron
EAF	electric arc furnace
EEDI	Energy Efficiency Design Index
ETP	*Energy Technology Perspectives*
EU	European Union
EV	electric vehicle
FiT	feed-in tariffs
FYP	Five-Year Plan
GBP	British pounds
GCCSI	Global Carbon Capture and Storage Institute
GDP	gross domestic product
GFEI	Global Fuel Economy Initiative
GHG	greenhouse gas
HDV	heavy-duty vehicle
HFO	heavy fuel oil
HVCs	high-value chemicals
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICE	internal combustion engine
IEA	International Energy Agency
IMO	International Maritime Organization
INDCs	Intended Nationally Determined Contributions
Istat	Italy National Institute for Statistics

ISI	Institut für System– und Innovation– forschung (Institute for Systems and Innovation Research)
IT	information technology
KAPSARC	King Abdullah Petroleum Studies and Research Center
KPIs	Key Performance Indicators
LBNL	Lawrence Berkeley National Laboratory
LCV	light commercial vehicles
LDV	light-duty vehicles
LED	light-emitting diode
LNG	liquefied natural gas
LPG	liquefied petroleum gas
NDCs	Nationally Determined Contributions
NPPs	nuclear power plants
NREL	National Renewable Energy Laboratory
OECD	Organisation for Economic Co-operation and Development
OEM	original equipment manufacturer
OGCI	Oil and Gas Climate Initiative
PHEV	plug-in hybrid electric car
PPP	purchasing price parity
PLDV	plug-in electric passenger light-duty vehicle
PNNL	Pacific Northwest National Laboratory
PV	photovoltaics
R&D	research and development
RD&D	research, development and demonstration
RDD&D	research, development, demonstration and deployment
RED	Renewable Energy Directive
RTS	Reference Technology Scenario
S&L	standards and labelling
SBIR	Small Business Innovation Research
SETIS	Strategic Energy Technologies Information System
SEC	specific energy consumption
SIRD	Survey of Industrial R&D
SMR	small modular reactor
SOx	sulphur oxide
T&D	transmission and distribution
TCEP	*Tracking Clean Energy Progress*
TCP	Technology Collaboration Programme
TFEC	total final energy consumption
UKIIF	United Kingdom Innovation Investment Fund
UN	United Nations
UNCTAD	United Nations Conference on Trade and Development

US	United States
USD	United States dollars
USPTO	US Patent and Trademark Office
VC	venture capital
WEO	*World Energy Outlook*
WLTP	Worldwide Harmonised Light Vehicles Test Procedure
WTW	well-to-wheel
y-o-y	year-on-year

Units of measure

EJ	exajoules
gCO_2/kWh	grammes of carbon dioxide per kilowatt hour
GJ	gigajoules
GJ/t	gigajoules per tonne
$GtCO_2$	gigatonnes of carbon dioxide
GW	gigawatt
GWe	gigawatts electrical
km	kilometres
L	litres
Lge	litres of gasoline equivalent
m^2	square metres
Mt	million tonnes
$MtCO_2$	million tonnes of carbon dioxide
MW	megawatts
MWh	megawatt hours
tCO_2	tonnes of carbon dioxide
TWh	terawatt hours

Regional and country groupings

Africa

Algeria, Angola, Benin, Botswana, Cameroon, Congo, Democratic Republic of Congo, Cote d'Ivoire, Egypt, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Libya, Morocco, Mozambique, Namibia, Nigeria, Senegal, South Africa, Sudan[1], United Republic of Tanzania, Togo, Tunisia, Zambia, Zimbabwe and other African countries and territories[2].

ASEAN (Association of Southeast Asian Nations) Brunei Darussalam, Cambodia, Indonesia, Lao People's Democratic Republic, Malaysia, Myanmar, Philippines, Singapore, Thailand and Viet Nam.

Asia

Bangladesh, Brunei Darussalam, Cambodia, 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[3].

China

Refers to the People's Republic of China, including Hong Kong.

European Union

Austria, Belgium, Bulgaria, Croatia, Cyprus[4], 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[5].

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.

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1. Because only aggregated data were available until 2011, the data for Sudan also include South Sudan.
2. Individual data are not available for: Burkina Faso, Burundi, 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.
3. Individual data are not available for: Afghanistan, Bhutan, Cook Islands, East Timor, Fiji, French Polynesia, Kiribati, Lao PDR, Macau, Maldives, New Caledonia, Palau, Papua New Guinea, Samoa, Solomon Islands, Tonga and Vanuatu. Data are estimated in aggregate for these regions.
4. [1.] Footnote by Turkey: The information in this document with reference to "Cyprus" relates to the southern part of the Island. There is no single authority representing both Turkish and Greek Cypriot people on the Island. Turkey recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Turkey shall preserve its position concerning the "Cyprus issue".
   [2.] Footnote by all the European Union Member States of the OECD and the European Union: The Republic of Cyprus is recognised by all members of the United Nations with the exception of Turkey. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.
5. Individual data are not available for: Antigua and Barbuda, Aruba, Bahamas, Barbados, Belize, Bermuda, British Virgin Islands, Cayman Islands, Dominica, Falkland Islands (Malvinas), French Guyana, Grenada, Guadeloupe, Guyana, Martinique, Montserrat, St.Kitts and Nevis, Saint Lucia, Saint Pierre et Miquelon, St. Vincent and the Grenadines, Suriname and Turks and Caicos Islands. Data are estimated in aggregate for these regions.

OECD Americas
Canada, Chile, Mexico and United States.

OECD Asia Oceania
Includes OECD Asia, comprising Japan, Korea and Israel,[6] 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.

6. 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.

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.

Nuclear power (page 28)

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 32)

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

CCS (page 34)

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

Figure 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 36)

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

Figure 19: Petrochemical feedstock energy use and blast furnace and coke oven energy use are included, as well as process and feedstock-related emissions.

Figure 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 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. Includes 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 40)

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 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 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 42)

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 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 44)

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 46)

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 48)

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 50)

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 in 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 52)

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 CO2 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 54)

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 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 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 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 56)

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 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 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 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 58)

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 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 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 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 60)

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 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 56: "Other renewable heat" includes geothermal heat across all sectors, solar heat in industry and all renewable heat sources in agriculture.

Figure 57: Source: AEBIOM (2016), *AEBIOM Statistical Report 2016*, AEBIOM, Brussels.

Energy storage (page 62)

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.

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Tracking Clean Energy Progress 2017

Energy Technology Perspectives 2017 Excerpt

Informing Energy Sector Transformations

Energy systems are undergoing substantial changes. Tracking the progress of clean energy is essential to achieve sustainable, secure and affordable energy and to assess collective progress towards long-term goals.

The IEA's annual *Tracking Clean Energy Progress* (*TCEP*) report highlights the overall status and recent progress in developing and deploying key clean-energy technologies. The report brings together broad IEA expertise, integrating the analysis from the *Energy Technology Perspectives* as well as the *Market Report Series*.

Each year, *TCEP* assesses the latest progress in technology and market developments, tracks overall progress, and recommends further actions. *TCEP* this year shows that only 3 of 26 identified clean energy technologies are on track to meet a sustainable energy transition (one more than last year). 15 technologies showed only some progress, and 8 are significantly off-track and in need of renewed action.

TCEP 2017 also includes a special section on tracking clean energy innovation, containing unique information on public and private investment in research, development, and demonstration. The special section highlights that total innovation investment needs to pick up to fulfill its important role of achieving secure and sustainable energy systems and delivering economic growth and reducing air pollution.

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