IRENA
International Renewable Energy Agency

GLOBAL ENERGY TRANSFORMATION

The REmap Transition Pathway

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This background report presents additional findings into the REmap transition pathway that is presented in the main report *Global energy transformation: A roadmap to 2050 (2019 edition)* available for download from **www.irena.org/publications**. For further information or to provide feedback, please contact IRENA at **info@irena.org**

About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

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Disclaimer

This background report presents technical findings for the status of the energy transition and the REmap transition pathway which are presented in the report *Global energy transformation: A roadmap to 2050 (2019 edition)*, available for download from:

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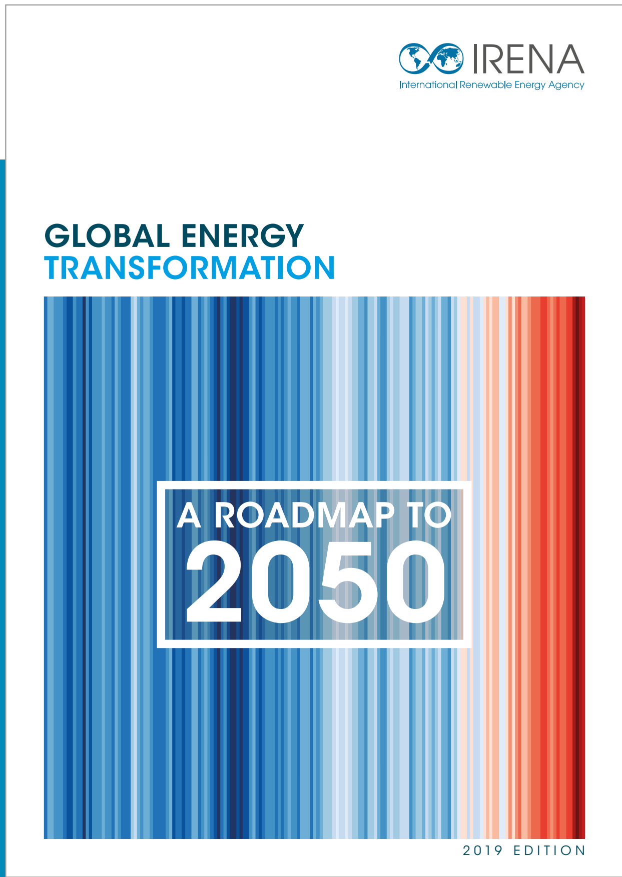
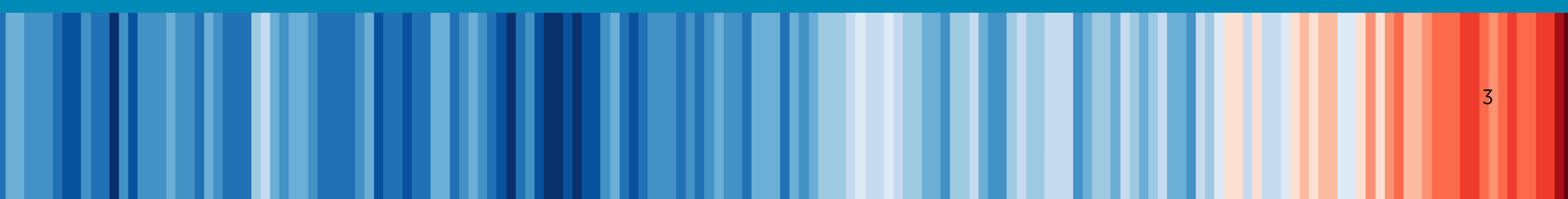


Annual global temperatures from 1850-2017
Warming Stripes, by **Ed Hawkins**, climate scientist in the National Centre for Atmospheric Science (NCAS) at the University of Reading.

The visualisation ***illustrates the changes witnessed in temperatures*** across the globe over the past century and more. The colour of each stripe represents the temperature of a single year, ordered from the earliest available data at each location to now. The colour scale represents the change in global temperatures covering 1.35°C.



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ABBREVIATIONS

°C	degrees Celsius
ASEAN	Association of Southeast Asian Nations
APEC	Asia-Pacific Economic Cooperation
bcm	billion cubic metres
bln	billion
BoS	balance of system
CAGR	compound annual growth rate
CCS	carbon capture and storage
CCUS	carbon capture use and storage
CHP	combined heat and power
CO_2	carbon dioxide
CSP	Concentrated Solar Power
DH	district heat
EJ	exajoule
ETS-Net	Energy Transition Scenarios Network
EU	European Union
EV	electric vehicle
EVSE	electric vehicles supply equipment
excl.	excluding
FCEVs	fuel cell electric vehicles
G20	Group of Twenty
GDP	gross domestic product
GJ	gigajoule
Gt	gigatonne
GW	gigawatt
GWh	gigawatt-hour
ICE	internal combustion engine
IEA	International Energy Agency
IPCC	intergovernmental panel on climate change
IRENA	International Renewable Energy Agency
kWh	kilowatt-hour
LCOE	levelised cost of energy
LCOH	levelised cost of hydrogen
LTES	long-term energy scenarios
LULUCF	land-use change and forestry
m^2	square metre
MENA	Middle East and North Africa
mln	million
Mt	megatonne
Mtce	megatonne of coal equivalent
Mtoe	million tonnes of oil equivalent
MW	megawatt
MWh	megawatt-hour
NDC	Nationally Determined Contribution
OECD	Organisation for Economic Co-operation and Development
ppt	percentage point
PV	photovoltaic
R&D	research and development
REmap	renewable energy roadmap analysis by IRENA
SEAD	Super-efficient Equipment and Appliance Deployment
SDG	Sustainable Development Goal
SDS	sustainable development scenario
SMR	steam methane reforming
t	tonne
TFEC	total final energy consumption
toe	tonne of oil equivalent
TPES	total primary energy supply
TWh	terawatt-hour
UK	United Kingdom
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
US	United States of America
USD	United States dollar
V2G	vehicle-to-grid
VRE	variable renewable energy
WACC	weighted average cost of capital
yr	year

1. STATUS OF THE ENERGY TRANSITION

1.1 Recent trends, 2010-2018

Countries must step up the pace of the energy transition. The world is starting from a baseline that it is still far away from what is needed for the decarbonisation of the energy sector. Recent trends are also not encouraging, as they show slow progress and slow improvements towards the final objective.

This chapter will demonstrate the need for acceleration by looking at five indicators:

- share of modern renewable energy in electricity generation
- energy intensity of gross domestic product (GDP) based on primary supply
- share of modern renewable energy in total final consumption
- electrification of final consumption
- annual emissions in the energy sector.

The table below shows a summary of the recent trends and required levels of ambition for each indicator according to the renewable energy roadmap analysis by IRENA (REmap) analysis, with respective compound annual growth rates (CAGR).

Table 1. Summary of recent trends and required levels of selected indicators

	Historical		Estimated	REmap Case		CAGR (%)	
	2010	**2016**	**2018e**	**2030**	**2050**	**2010–2016**	**2016–2050**
Share of renewable energy in electricity generation (%)	20%	24%	26%	57%	86%	+3.1%	+3.8%
Energy intensity of GDP based on primary supply (MJ/USD-PPP, 2011)	5.9	5.1	5.0	4.6	2.4	-2.3%	-3.2%
Share of modern renewable energy in total final energy consumption (%)	10.1%	9.8%	10.5%	28%	66%	-0.4%	+5.8%
Electricity share of total final energy consumption (%)	18%	19%	19%	29%	49%	+1.1%	+2.9%
Annual energy-related emissions (Gt CO_2/year)	29.7	33.5	34.3	24.9	9.7	+2.0%	-3.5%

Electrification, energy efficiency improvements and the deployment of renewables must all accelerate throughout the years up to 2050 to achieve the aims of the Paris Agreement.

Despite the very slow progress, there are two positive trends. First, in the power sector, the share of renewable energy in electricity generation has been increasing steadily. Renewable electricity generation share increased from around 20% to nearly 24% from 2010 to 2016 (or 3.1% per year on average) (IEA 2018c). An estimate for 2018 indicates a further increase to 26%. As the REmap analysis shows in the next chapter, the share of renewable energy in electricity generation would need to climb to 86% in 2050.

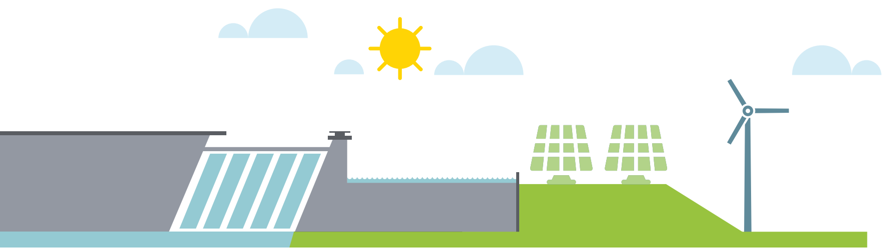
The second positive sign is the consistent improvement in the energy intensity of GDP. Energy intensity has declined from 5.9 MJ/USD-PPP2011 to 5.1 MJ/USD-PPP2011 from 2010 to 2016, with another slight decline estimated for 2018, according to IRENA's estimates, though the decline in 2018 was lower than in the previous two years. To meet the goals of the REmap scenario towards 2050, the energy intensity would have to decline further to reach 2.4 MJ/USD-PPP2011 in 2050.

Other indicators, however, do not show positive trends. The share of renewable energy in final energy consumption in 2016 stayed at roughly the same levels as in 2010, barely moving from around 10% (IEA 2018c). Estimates from IRENA for 2018 show slight signs of improvement, with the renewable share of final consumption growing to 10.5%. This share should be brought up to over 65% in 2050.

Electrification of final uses of energy has mostly stagnated in the past seven years, with a very slight upward trend from 2010. In 2016, electrification reached close to 19% of total final energy consumption. It would have to grow to nearly 50% by 2050, according to the REmap Case.

The trends above have resulted in a negative impact on greenhouse gas emissions in the energy sector. In the period from 2010 to 2016, global CO_2 emissions from the energy sector increased by almost 13%, from 29.7 Gt CO_2 to 33.5 Gt CO_2 (IEA 2018a). Estimates indicate that emissions continued to rise and may have reached a new record high of 34.3 Gt CO_2 in 2018 (Carbon Brief 2018). These emissions levels are a far cry from what is needed to meet the goals of the Paris Agreement. According to the REmap scenario, emissions would have to drop to slightly below 10 Gt CO_2 by 2050 – a more than 70% reduction from 2016 levels.

Meanwhile, investment in renewable energy declined in 2017 after several years of growth (IEA 2018f). Despite an increase in investment in energy efficiency, the combined investment in renewable energy and energy efficiency showed a slight reduction of 3% in 2017, compared to the previous year. That is unfortunate in a world where a strong acceleration in investments in energy efficiency and renewable energy is needed. Partly because of that decline and partly due to a modest increase in fossil fuel investment, the share of investment in fossil fuels in the energy supply increased in 2017 (IEA 2018f). This was the first increase since 2014. Also, the global fleet of coal-fired power plants continued to expand in 2017, in spite of a decline in new added capacity and a high number of retirements of existing plants (IEA 2018f).



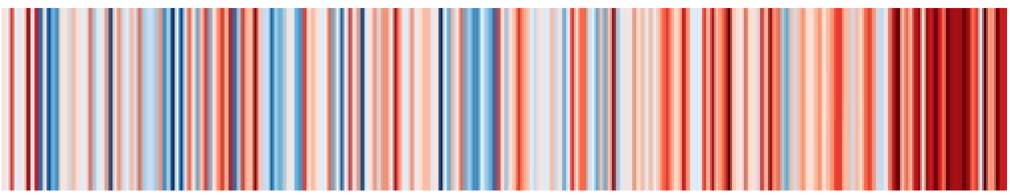
1.2 Future Developments: The Reference Case towards 2050

The Reference Case has improved since IRENA's 2017 analysis, but not nearly enough to meet the Paris climate goals. The Reference Case is the scenario that takes into account the current and planned policies of countries. It includes commitments made in the Nationally Determined Contributions (NDCs) and other latest planned targets. It presents a perspective based on governments' current projections, energy plans and policies.

Many governments have strengthened efforts to reduce national energy-related emissions in the last few years. The Reference Case indicates a fall in energy-related CO_2 emissions as a result of these revised policies and plans, including NDCs. This was an improvement relative to the 2017 analysis in the 2018 analysis, which found that CO_2 emissions would be slightly lower in 2050 and indicated that NDCs and the rapidly improving costs and performance of renewable energy technologies are influencing long-term energy planning and scenarios. In this year's analysis, energy-related annual emissions in the Reference Case are projected to decline slightly to 33 Gt CO_2 in 2050, a decline from the 35 Gt CO_2 projected in the previous year's analysis. However cumulative emissions over the period to 2050 have only declined slightly, due in large part to emissions levels in the 2020-2030 timeframe being higher than in the last analysis, offsetting the lower emissions that occur towards 2050.

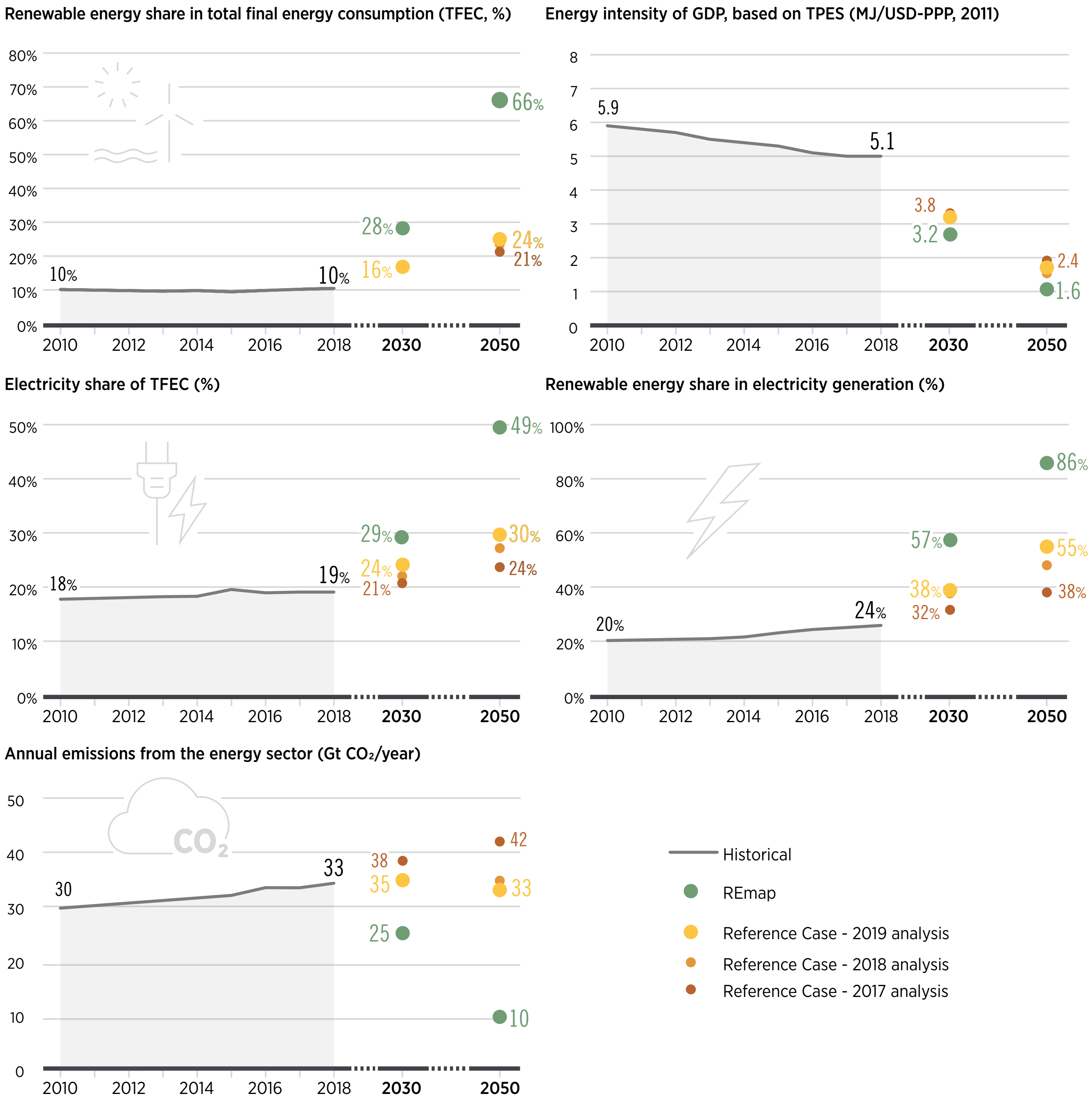
The same positive trends towards 2050 can be seen in the other indicators. Renewable energy shares, energy intensity and electrification all improve in the current Reference Case analysis in 2050, compared with those of 2018 and 2017.

The following charts show the trends for each of the ten indicators in the period 2010 to 2016, with estimates for 2017 and 2018. The charts also show how the level of ambition in each indicator evolved when the Reference Cases from previous years (2017 and 2018) are compared with the Reference Case of the current analysis – showing a general improvement in the long-term prospects. It also shows the gap compared to the REmap Case, emphasising the urgent need for accelerating the transition if the world is to meet the climate goals set out in the Paris Agreement. In the charts below, the solid blue lines show the evolution from 2010 to 2016 and the estimated data for 2017 and 2018. The red dots, black squares and red crosses show the evolution of the Reference Case for the years 2017, 2018 and 2019, respectively – indicating, in most cases, an increasing ambition from countries, particularly in the year 2050. The blue dots show the level of ambition needed according to the REmap Case.



Annual temperatures in central England from 1772-2017
The colour scale goes from 7.6°C (dark blue) to 10.8°C (dark red)

Figure 1. Monitoring the energy transition, mixed indicators



Current plans – as reflected in Nationally Determined Contributions to meet climate goals – point in the right direction yet still fall short of what is needed to meet international climate goals. Serious action is needed to accelerate the energy transition.

1.3 Recent developments pointing the way forward

Additions to renewable power capacity continue to exceed fossil fuel generation additions by a widening margin. In 2017, the sector added 167 GW of renewable energy capacity globally, a robust growth of 8.3% over the previous year and a continuation of previous growth rates since 2010 averaging 8-9% per year. For the sixth successive year, the net additional power generation capacity of renewable sources exceeded that of conventional sources. In 2017, 94 GW were added by solar photovoltaic (PV) and 47 GW by wind power (including 4 GW of offshore wind). Renewable power generation accounted for an estimated quarter of total global power generation in 2017, a record (IRENA 2018). In 2018, an estimated 160 GW of solar and wind were added globally (GWEC 2019; BNEF 2019).

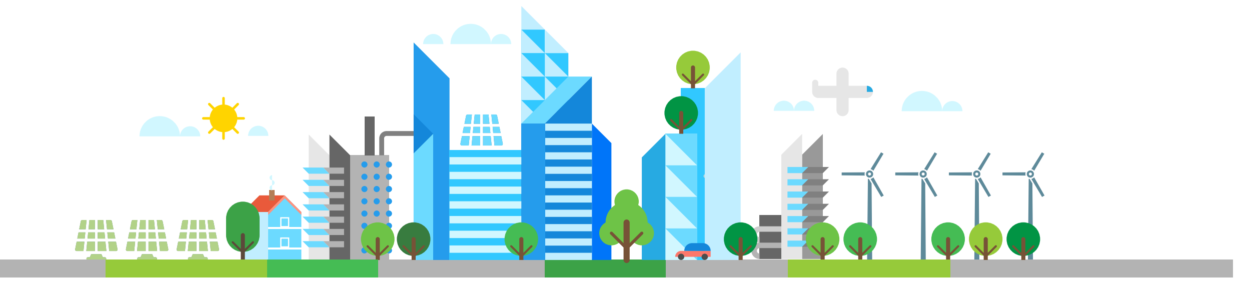
The integration of variable renewable energy (VRE) in power systems continues to expand. Countries such as Denmark, Germany, Portugal, Spain and Uruguay have proven the feasibility of managing annual VRE shares higher than 25% in power systems. An increasing number of subregions and even entire countries have managed VRE shares close to 100% for short periods of time (IRENA 2019b):

- Renewables are projected to have produced 33% of total power generation in the United Kingdom and 40% of total power generation in Germany and Spain in 2018 (Energy Reporters, 2018; FT, 2019e; PV Magazine, 2019), and instantaneous generation can reach even higher levels. Chile is undergoing a renewable energy boom and for the last few years has been one of the largest renewables markets in Latin America (PV-Tech, 2018), and Morocco is pioneering its own boom, with renewable power providing 35% of its electricity in 2018 (MoroccoWorldNews 2019).
- In Denmark, the VRE capacity penetration has been more than 40% since 2014, reaching 53% in 2017, with most of it coming from wind energy. The country has a target of achieving 100% renewables in the energy sector by 2050, with 50% coming from wind electricity.
- In the Republic of Ireland and Northern Ireland, VRE accounted for almost 30% of electricity demand in 2017, with wind providing most of it. In January 2015, the island experienced a maximum instantaneous wind penetration of 66.2%, and the region has a target of achieving 40% renewable energy penetration by 2020, mostly from wind.
- Texas is the leading US state for wind capacity, with wind accounting for 14.8% of the generation mix in 2017. Solar accounted for 1% of the state's generation mix in 2016. Texas is expected to see 9 GW of planned VRE additions in 2018/19, increasing total VRE to 40%, or 29 GW, by the end of 2019.
- In California, almost 20% of the generation mix was from wind and solar in 2017. There is a large share of distributed renewable resources on the grid, with 5 900 megawatts (MW) of rooftop solar PV capacity. The state has a target of reaching 33% renewable energy generation by 2020, 50% by 2026 and 60% by 2030.
- The South Australia subsystem reached 48.4% of power generation from wind and solar sources in 2017, with wind accounting for 39.2% and rooftop solar for 9.2%. More than 30% of households have a PV system installed, for a total of 781 MW. The target for the region is to reach 50% renewables in the generation mix by 2020, and 75% by 2025.
- In Uruguay, 48.4% of power generation came from wind and solar in 2017. Together with hydropower and biomass, renewable generation accounted for 98% of the total electricity.

- Variable wind and solar generation was 25% in 2017 in Germany. Total renewable energy generation (hydropower, wind, solar and biomass) was up 15% year-on-year to 210 terawatt-hours (TWh), or 38.2% of the 2017 total. The country has a target of 65% renewables in electricity by 2030.
- In Brazil, the Northeast region of the country saw a record-breaking 70% of its electricity demand being met by wind power in a day of 2018, when the capacity factor of wind turbines averaged over 71% during the day.

More and more companies around the world are voluntarily and actively investing in self-generation and procuring renewable energy. Global electricity markets are constantly evolving to meet the growing demand for renewable energy required by all categories of consumers, including companies. IRENA estimates that at the end of 2017, the corporate renewable electricity market reached 465 terawatt hours (TWh), representing approximately 3.5% of total electricity demand and 18.5% of renewable electricity demand in the commercial and industrial sectors. Corporations can significantly contribute to the needed acceleration of renewable energy deployment through more active and direct procurement. IRENA estimates that the production of renewable energy for self-consumption was 165 TWh in 2017 (IRENA 2018c). Direct investment for self-generation takes place in almost every country that permits some form of grid connection at a rate of compensation, through net metering or feed-in tariff schemes. As of 2016, 83 countries had feed-in tariffs or premium payment policies in place, and 55 countries had net metering policies (REN21 2017).

Companies are also changing business plans to move away from carbon-intensive activities and fuels. Recently, Glencore announced that it would limit coal production to support global efforts to combat climate change. The group further recognised climate change science as set out by the United Nations Intergovernmental Panel on Climate Change (IPCC) and stated its support of the goals set out by the Paris Agreement on limiting global temperature rises. This is one of many examples of large corporations, even those with high stakes in carbon-intensive activities, that are shifting their long-term strategies away from carbon emissions. Glencore also stated that it is strongly positioned to support the move to a lower-carbon economy thanks to its copper, cobalt and nickel businesses, because those elements are used in electric vehicles and battery storage (FT, 2019a). That decision comes at the same time as governments and other businesses commit to phase out coal. As of late 2018, 30 national governments, 22 subnational governments and 28 businesses had committed to phase out coal by 2030, under the Powering Past Coal Alliance (Energy Post 2019). Germany agreed earlier this year to completely phase out coal use by 2038, a landmark decision considering the country is amongst the world's largest coal consumers. More recently, the government of Norway mandated its wealth fund to partially divest from some oil and gas stocks in the exploration sector (Bloomberg 2019). There are also signs that even the oil majors are considering getting more into the electricity business. Royal Dutch Shell recently said it could develop a power business and mentioned that it could become one of the largest electricity companies globally by 2030 (FT, 2019d).



A growing number of cities have set targets to increase the share of renewables in their energy mix. Many are using these targets to align policies across infrastructure networks (water supply, transport, electricity, heat, waste, etc.) to create synergies and to align renewable targets with climate and efficiency targets. In some countries, cities have exceeded national targets. Malmö, Vancouver and Canberra, for example, are working towards 100% renewable energy (IRENA 2018g). In Japan, as of the end of 2015, 14 cities had formed companies to generate renewable power from local resources, such as town-owned PV systems. Following the full deregulation of Japan's electricity market beginning in 2016, the government now aims to have 1 000 such city-operated power companies established by 2021 (WSJ 2015). The C40 initiative adds momentum to the change. The initiative is a network of the world's megacities, representing over 700 million citizens and one-quarter of the global economy, committed to addressing climate change. It supports cities to collaborate effectively, share knowledge and drive meaningful, measurable and sustainable action on climate change (C40 2018).

Dramatic cost reductions, technology advancements and enabling policies have driven the adoption of Distributed Energy Resources (DER) technologies globally. IRENA estimates that approximately 133 million people were served by rural off-grid technologies in 2016, with 9 million connected to renewable mini-grids and 124 million utilising solar lighting and solar home solutions. Small hydro mini-grids are the most widely deployed systems, growing to over 509 MW in 2017 and providing electricity to over 6 million rural users. Over the last decade, PV mini-grids have also rapidly grown from 11 MW of capacity in 2008 to 308 MW in 2017, reaching over 2.1 million people (IRENA 2018e).

The prospects of electrification in transport continue to look increasingly good. In 2018, an estimated 2.1 million new plug-in electric vehicles were sold globally (INSIDEEVs 2019). This would establish a new record level and is a solid increase from previous year sales of 1.2 million units (EV Volumes 2018). China and the United States, followed by Europe, continue to be the largest markets. Sales of electric vehicles have grown rapidly in the last five years from just above 300 000 units in 2014. Other electric vehicles, including buses, delivery trucks and two- and three-wheelers, also saw their market penetration grow very substantially in Asia. Over 1 billion light electric vehicles could be on the road by 2050 if the world starts soon on the path to decarbonisation as detailed in this report. Electrification of transport is now also being tried in sectors which many believed would not be impacted by it. For example, Avinor, the public operator of Norway's airports, has a goal of using electric aircraft for all flights of up to 1.5 hours long by 2040 (Avinor 2018). Ships are being electrified and batteries have been introduced on ferries in Norway, for example, while hydrogen is being considered in Germany for river freight shipping. In California, Pacific Gas & Electric (PG&E) and BMW have been testing electric vehicle (EV) charging as a grid resource since 2015. Last year, they did a pilot aligning smart EV charging with renewable energy generation, creating a stronger case for electric vehicles as a grid resource (GTM 2018).

A new suite of mobility services may reshape the transport sector. In the transport sector, the emergence of new business models that focus on mobility services rather than car ownership – such as car sharing, Uber and autonomous vehicles – could transform the way private and public mobility operates. These services might result in significant improvements in the efficiency of resource utilisation and fuel demand, with fewer vehicles lying idle at any time and greater optimisation of travel. They might also become truly reliable and affordable alternatives to private car ownership, offering an effective solution to the road congestion that increasingly plagues large urban centres (IRENA 2019b).

The prospects for higher electrification rates in other end-use sectors have also improved. In some Nordic countries, heat pumps already account for more than 90% of the sales of space heating equipment (EHPA 2017). In Sweden, for example, E.ON's Ectogrid technology enables a number of buildings to be connected to a thermal grid, using heat pumps to supply the necessary heat. Heat or cooling flows as needed among the buildings, controlled by a cloud-based management system. The approach reduces heating bills by 20% (Ectogrid 2018). In northern England, a project called HyDeploy is launching a four-year trial to inject hydrogen produced via electrolysis into a number of existing gas grids. That will reduce cooking and heating emissions without the need for new end-use appliances (HyDeploy 2018).

Policies and programmes aimed at further improvements in energy efficiency in the end-use sectors are another active area. The Super-efficient Equipment and Appliance Deployment (SEAD) Initiative, for instance, is a voluntary collaboration among governments working to promote the manufacture, purchase and use of energy-efficient appliances, lighting and equipment worldwide (SEAD n.d.). Under the initiative, various member governments have been able to develop and improve national policies to help raise the ambition and increase the impacts of their appliance energy efficiency programmes. Under SEAD, with the leadership of Lawrence Berkeley National Laboratory (Berkeley Lab), countries like Chile, Indonesia and South Africa and have been able to develop new targets and standards for energy efficiency. Examples include a national roadmap – the 10GW Energy Efficiency Plan – to determine activities that can help drive key energy efficiency policies and programmes in Indonesia; new energy efficiency standards for air conditioners in Chile; and analyses showing potential energy savings from new energy efficiency programmes in Argentina, Mexico and South Africa.

Industry is the most challenging of the three major sectors to decarbonise. Despite the challenges, however, countries and companies are seeking solutions. The use of alternative, biomass-derived fuels in the cement industry is one solution adopted in many countries. The development of novel less carbon-intensive processes is also happening. For example, the Swedish Energy Agency is co-financing a pilot initiative called HYBRIT that will use hydrogen from hydro and wind power to make steel. The goal is to make the production of steel fossil-free by 2035, at a cost that is competitive with traditional steel production. That initiative alone has the potential to cut Sweden's total carbon dioxide emissions by 10% (HYBRIT 2018). Decarbonisation of heat supply in industry through solar thermal technologies, thermal storage and power-to-heat solutions also has reached a well-developed stage. These approaches are now seen to have the potential to supply low-cost, efficient and carbon-free heat for industrial applications. As Kraft Foods in the United States found, using heat pumps to heat water, combined with heat waste recovery from refrigeration systems, offers significant cost reductions. The company saved more than 14 million gallons of water and USD 260 000 annually (Emerson 2012).

2 PATHWAY FOR THE TRANSFORMATION – THE REMAP CASE

The global energy transformation requires significant changes in the global energy sector. As this chapter lays out, renewable energy and energy efficiency are the core elements of the transition. The transition offers an important synergy between increasingly affordable renewable power technologies and the wider adoption of electric technologies for end-use applications, especially in transport and heat. While steps have been taken in recent years in the right direction, a very significant acceleration is needed of an energy transformation that is centred on renewable energy deployment, electrification and efficiency. This chapter goes into more detail on these topics. It presents an energy pathway from two scenario perspectives, the Reference Case and the REmap Case.

Figure 2. The Reference and REmap Cases

Reference Case

This scenario considers current and planned policies of countries. It includes commitments made in Nationally Determined Contributions and other planned targets. It presents a perspective based on governments' current projections and energy plans.

REmap Case

This scenario includes the deployment of low-carbon technologies, based largely on renewable energy and energy efficiency, to generate a transformation of the global energy system that limits the rise in global temperature to well below 2 degrees Celsius above pre-industrial levels. The scenario is focused on energy-related carbon dioxide emissions, which make up around two-thirds of global greenhouse gas emissions.

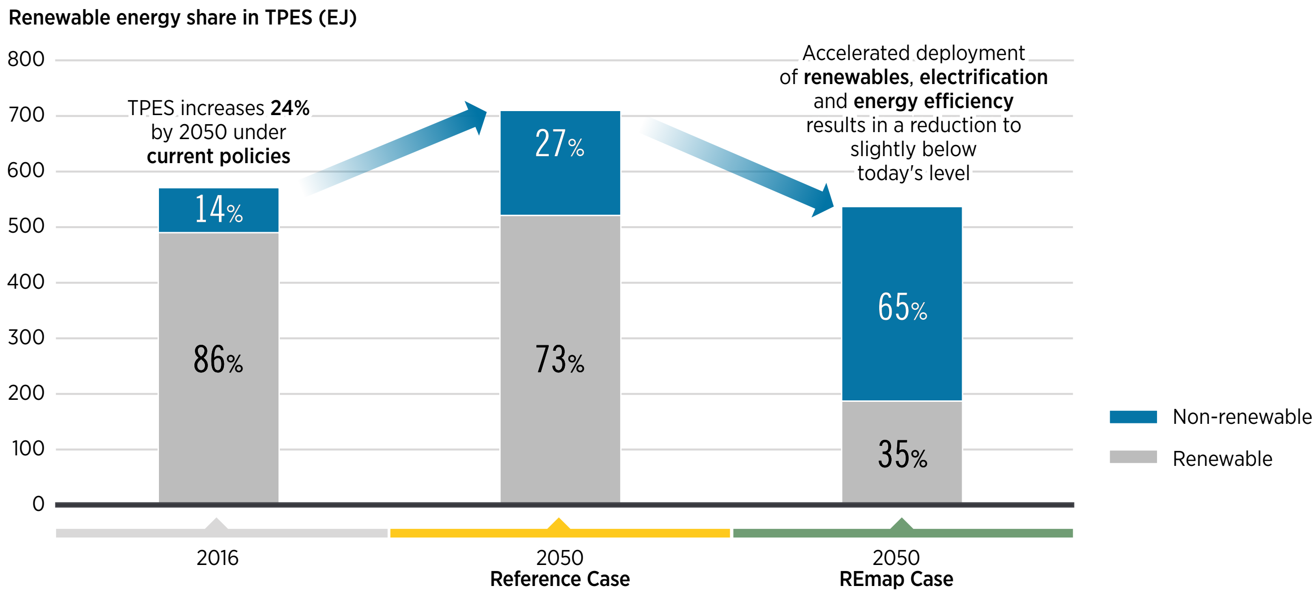
2.1 Global pathway and electrification with renewables

The total share of renewable energy would need to rise from around 14% of total primary energy supply (TPES) in 2016 to around 65% in 2050. Under current and planned policies in the Reference Case, this share increases only to 27%, while under the REmap Case it increases to 65%. Renewable energy use in absolute terms, including traditional uses of biomass, would more than quadruple from 81 exajoules (EJ) in 2016 to 350 EJ in 2050 in the REmap Case. The renewable energy mix would change, with the share of renewables coming from bioenergy decreasing from two-thirds to one-third, and with a much higher share of solar- and wind-based energy in the REmap Case in 2050.

TPES would also have to fall slightly below 2016 levels, despite significant population and economic growth. In the period from 2010 to 2016, global primary energy demand grew 1.1% per year. In the Reference Case, this is reduced to 0.6% per year to 2050, whereas in REmap the energy demand growth turns negative and results in a decline of 0.2% per year to 2050.

Figure 3. The global energy supply must become more efficient and more renewable

TPES, renewable and non-renewable share for Reference and REmap Cases, 2016-2050 (EJ/yr)



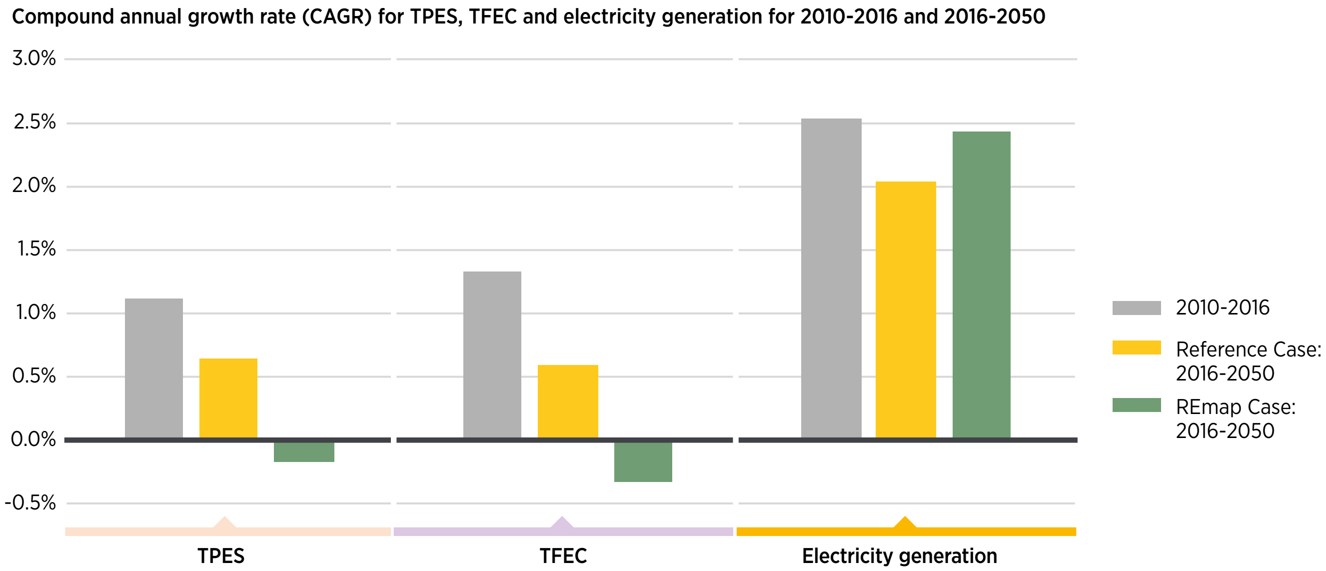
Under current and planned policies, the world's energy supply looks set to grow nearly a quarter by 2050, with the share of renewables reaching just 27%. To meet agreed global climate goals, renewables would need to provide two-thirds of the world's energy supply, with improved energy efficiency bringing total energy supply back to less than today's levels.

The REmap Case would result in two major shifts. First, energy efficiency increases due to the increase in renewable electrification, especially in transport and heat. The increasing use of renewable electricity reduces inefficient fuel consumption. In addition, structural changes – such as mode shifting, the increasing share of the service sector in value added in GDP and growth in the circular economy – improve the productivity of the economy.

Second, the electricity mix would be transformed, and the carbon intensity of electricity drops by 90%. The result is that the power sector in the REmap Case would more than double in terms of generation – to over 55 000 TWh (up from around 24 000 TWh today). The sector would see wide-scale deployment of renewable energy and increasingly flexible power systems, supporting integration of variable renewable energy (VRE). The share of renewable energy in the power sector would increase from 24% in 2016 to 86% in 2050. This transformation would require new approaches to power system planning, system and market operations, and regulation and public policy.

Figure 4. Growth rates of TPES, TFEC and electricity generation

Compound annual growth rate (CAGR) for TPES, TFEC and electricity generation



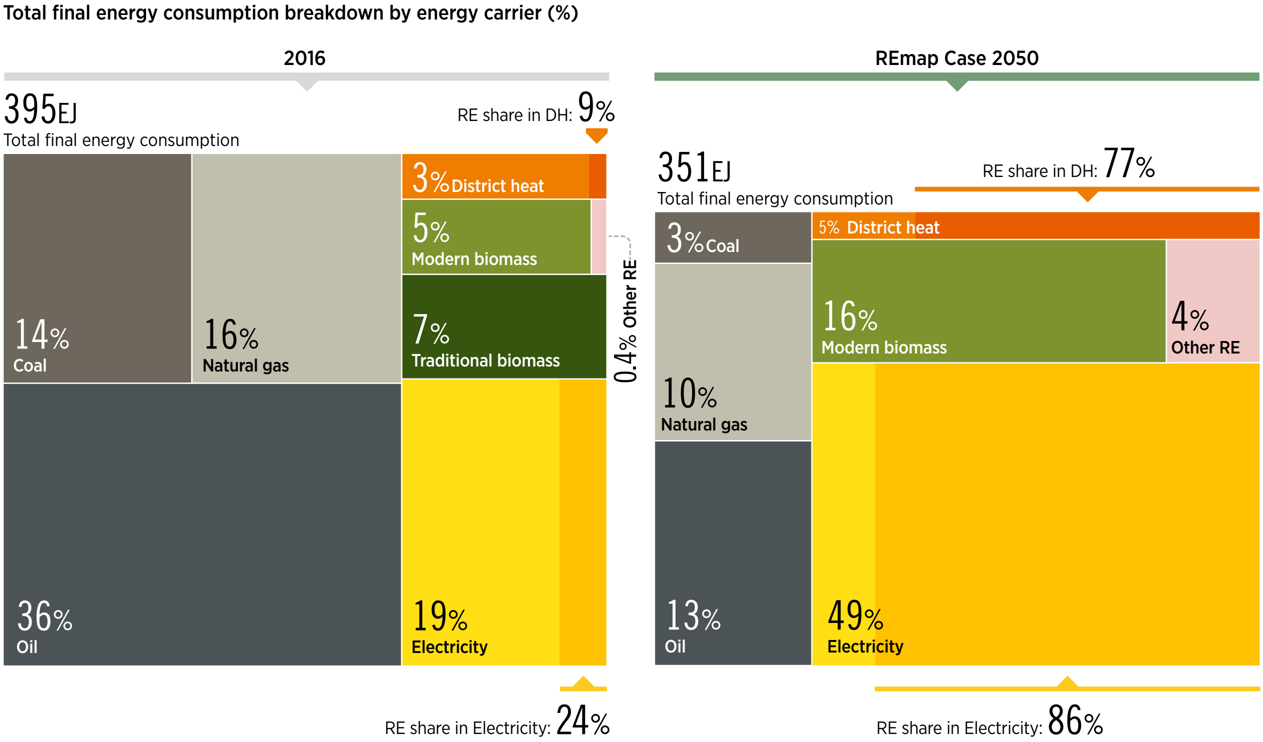
Electricity generation would grow while total energy supply and demand would fall. As end uses become more electrified, power generation would need to grow by 2.5% per year, while total energy supply and consumption would need to decrease by 0.2% and 0.4% per year, respectively.

Increasingly, electrification with renewables is seen as a major solution, and the contribution of renewable electricity will be the single largest driver for change in the global energy transformation. The share of electricity in total final energy use would increase from just 20% today to 49% by 2050. The share of electricity consumed in industry and buildings would double to reach 42% and 68% in 2050, respectively, and in transport it increases from just 1% today to over 40%. Likewise, other subsectors or activities would also see significant increases in the share of electricity use. Some of the largest growth would be seen in the buildings sector for space heating and cooking, and in the transport sector for passenger and road freight.

Despite the growth of renewable electricity use in end-use sectors, direct use of renewable energy would still be responsible for a sizeable proportion of energy use in

Figure 5. Electricity becomes the main energy carrier in energy consumption by 2050

Breakdown of total final energy consumption (TFEC) by energy carrier in 2016 and REmap Case 2050 (EJ)



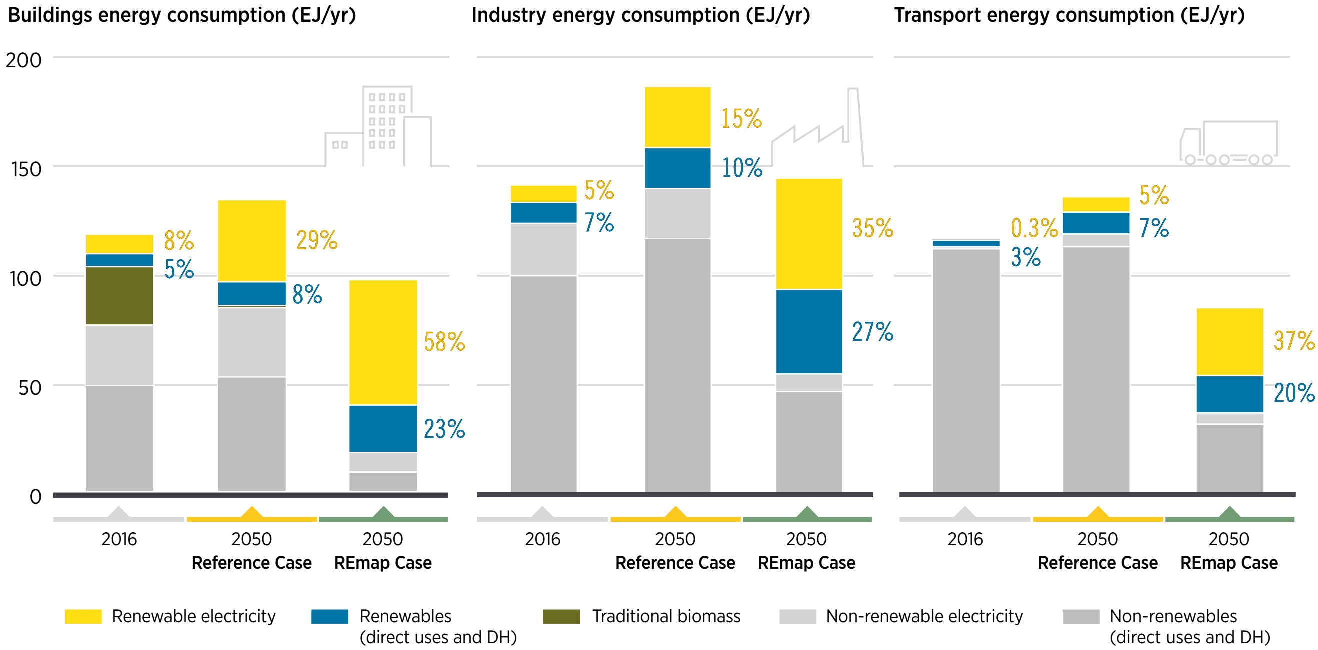
Electrification of energy services in transport and heating would need to increase substantially by 2050. When electricity becomes the world's main energy carrier, it would be mostly supplied from renewables (86%).

industry, buildings and transport. Much of it would involve direct use of biomass, with sizeable contributions from solar thermal and some use of geothermal and other renewable sources.

Largely due to increased renewable electrification and direct renewables use, the share of renewable energy in TFEC would also rise considerably. The Reference Case sees an increase in the share of renewable energy in final energy consumption from 17% in 2016[1] to 25% by 2050. The REmap Case results in a much higher share of 66%. Therefore, more than a six-fold acceleration in the percentage point increase in renewable energy share would be needed (from around 0.25 ppt/yr increase in the Reference Case, to almost 1.5 ppt/yr) to raise the overall share from 17% to 18.5% in the first year and then incrementally, to reach 66% in 2050.

Figure 6. Renewable energy shares increase in all end-use sectors

Renewable and fossil energy consumption in buildings, industry and transport sectors; Reference and REmap cases, 2016 and 2050 (EJ/yr)



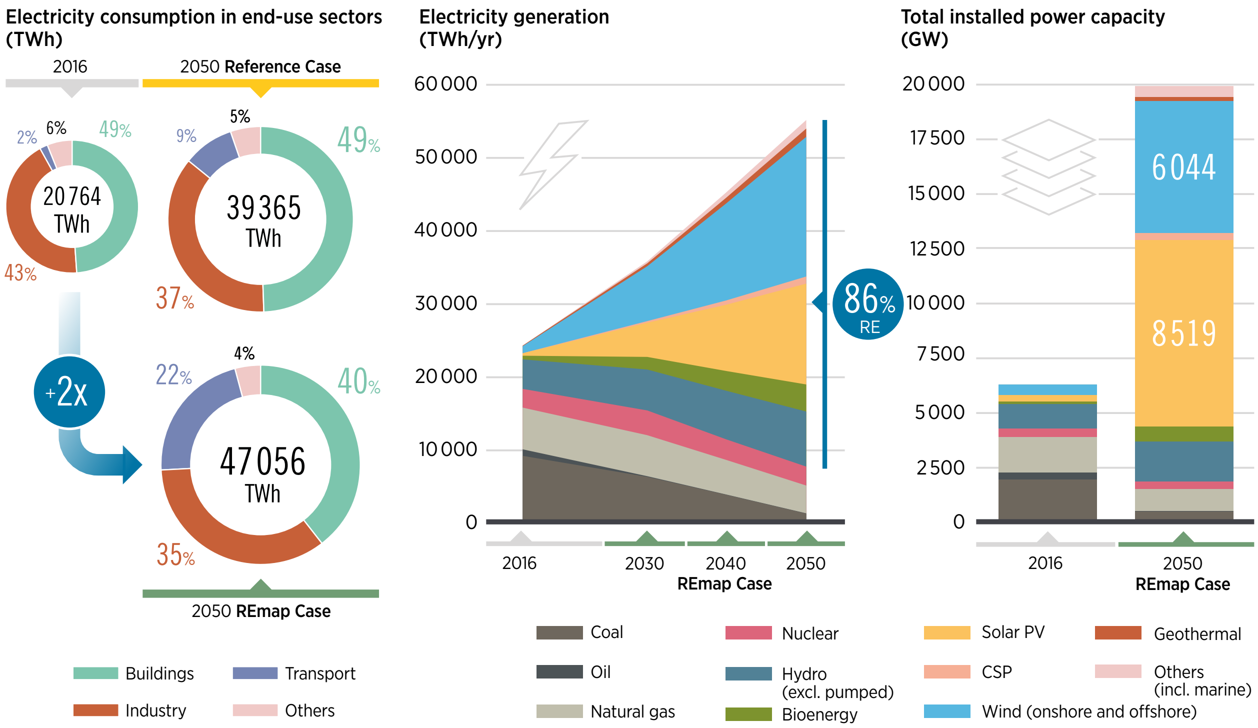
Note: Hydrogen in transport and industry sectors is included in electricity part. "Non-renewable" includes direct uses of fossil fuels (*e.g.,* for heating, cooking, transport, *etc.,*); "Renewables" includes direct uses of renewables (*e.g.,* solar water heating) and district heating with renewables.

Renewable energy and energy efficiency, in combination with electrification, are the key ingredients to ensure a sustainable energy future. By 2050, renewables could dominate the transport and buildings sectors reaching 57% and 81% of the sectors' total final energy consumption, respectively. Renewables would cover one-quarter of final energy use for industry. In all sectors, electricity would account for the largest share of renewable energy use, complemented by direct uses of biomass, geothermal and solar thermal.

1 For 2016, if traditional uses of bioenergy are excluded, the share of modern renewable energy is around 10%.

Figure 7. Wind and solar will dominate electricity generation

Electricity consumption by sector, electricity generation (TWh/yr) and power capacity mix (GW)



Note: CSP refers to concentrated solar power

Renewables would reach 86% of total electricity generation by 2050. Nearly two-thirds of the world's electricity would come from solar and wind power, with installed wind capacity exceeding 6 000 GW and solar capacity of more than 8 500 GW in 2050. Hydropower and geothermal generation would also grow, further contributing to decarbonisation.

The energy intensity of the global economy would fall by two-thirds by 2050 in the REmap Case. In recent years, energy intensity has been improving at around 2.3% per year (IEA 2018d); however it is projected to have decreased to just above 1% in 2018. Nonetheless, the Reference Case projects that this will accelerate to 2.4% per year. The REmap Case results in an improvement of 3.2% per year.

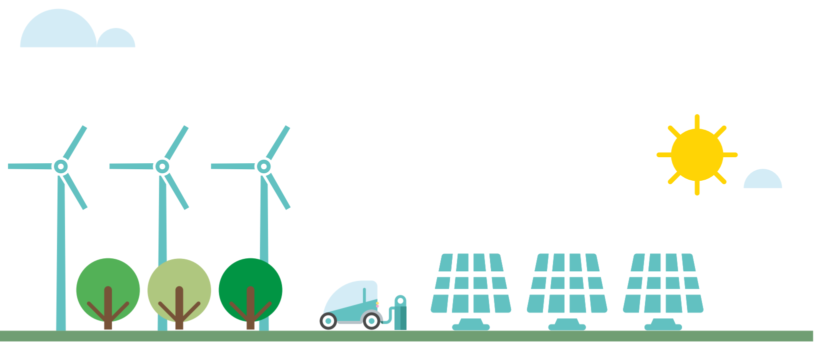
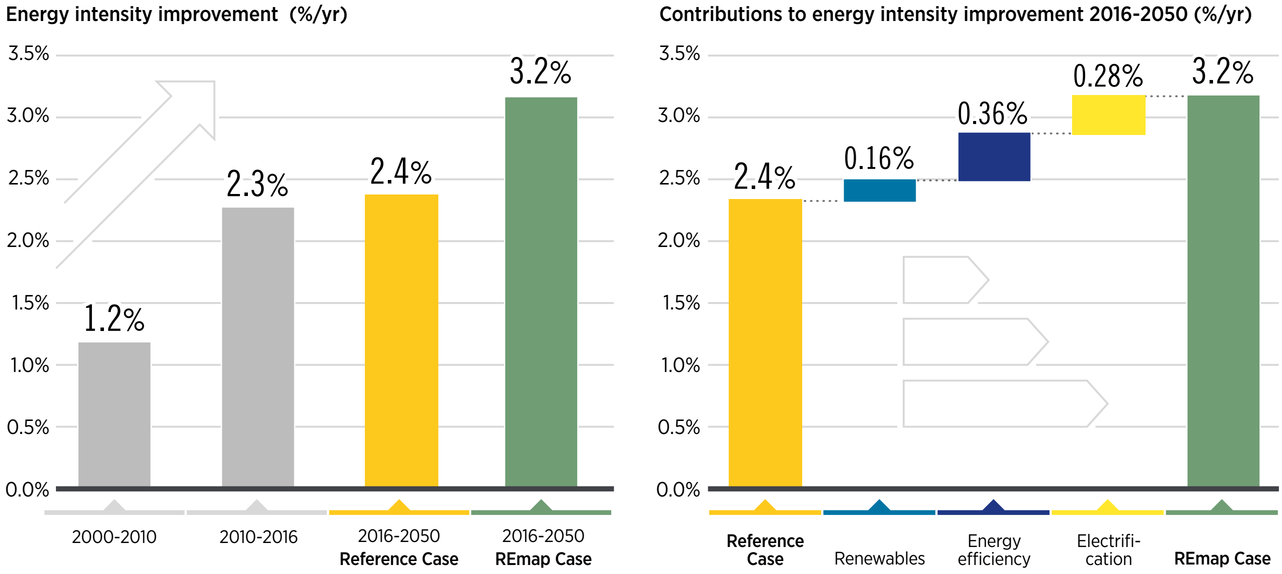


Figure 8. Energy intensity improvements are driven by electrification, renewable energy and energy efficiency

Energy intensity improvement (%/yr) and its contributions in the Reference and REmap Cases, 2016-2050



Note: The categories listed in the energy intensity improvement represent an aggregated sum of measures in power and end-use sectors under each technology option. "Renewables" implies energy intensity improvements achieved with respect to deployment of renewable technologies in the power sector (wind, solar PV, *etc.*,) and in end-use direct applications (solar thermal, *etc.*,). "Energy efficiency" contains efficiency measures deployed in industry, buildings and transport sectors (*e.g.*, improving insulation of buildings; more efficient appliances, *etc.*,). Energy efficiency also includes structural changes which encompass mode shifts, such as the service sector increasing share in GDP and consuming less energy compared to other industrial sectors. "Electrification" denotes electrification of heat and transport applications such as deploying heat pumps and EVs. The Reference Case already considers some improvements due to structural changes, but in REmap additional reductions are achieved.

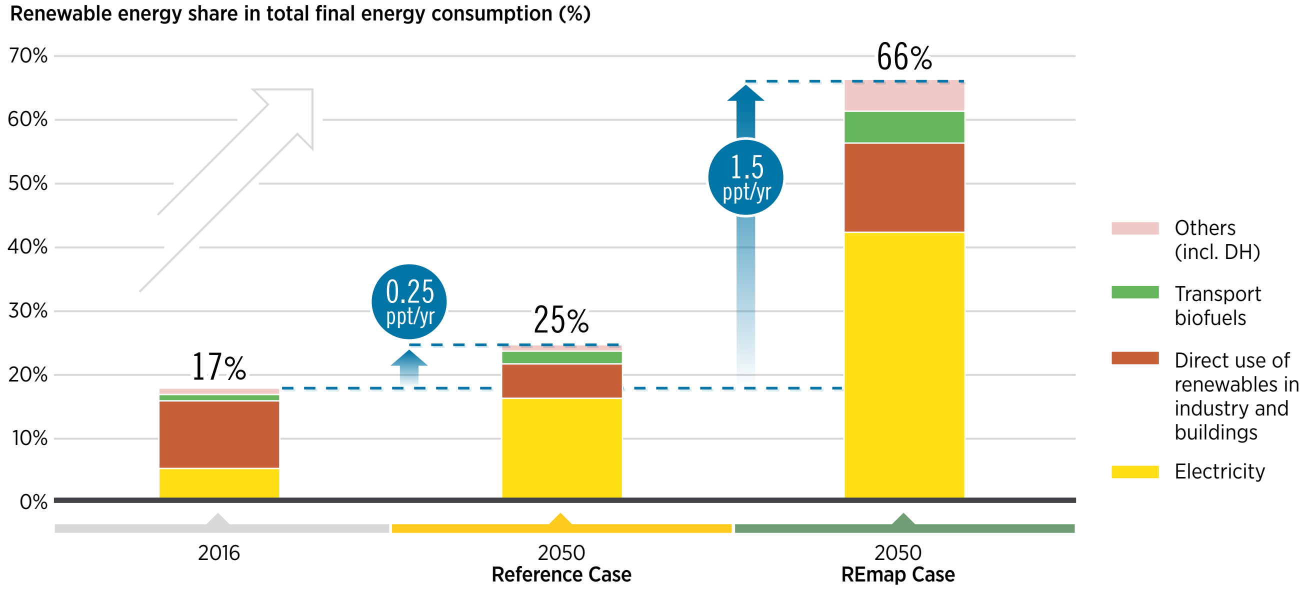
Even though almost half of final energy use would be sourced from electricity, fuels and other direct uses of energy would still make up half of energy demand. In the transport and industry sectors, the share of electricity increases to around 40% by 2050, with most of the energy still coming from fuels. Bioenergy can still play an important role in transportation and in process heat generation.

The rate of improvement for energy intensity from 2.4% to 3.2% per year is driven in part by electrification and technical energy efficiency improvements in energy conversion and use.

The substantive electrification of transport and heat demand powered by renewables rapidly brings down inefficient fossil fuel consumption.

Figure 9. Growing share of renewables in final energy consumption

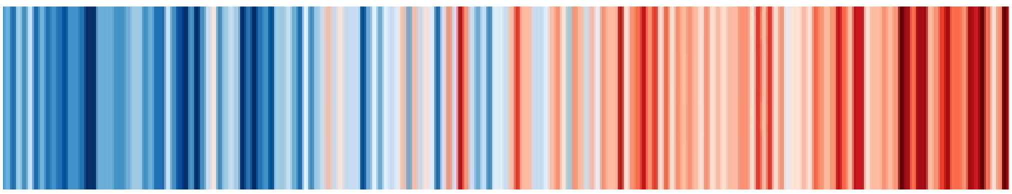
Renewable energy share in TFEC (%), Reference and REmap Cases, 2016, 2050



Note: DH refers to district heat

The share of renewables in total final energy consumption (TFEC) needs to ramp up six-fold – from a historical average of 0.25 percentage points per year to almost 1.5 percentage points per year.

Modern bioenergy can play a vital role in the energy transition if scaled up significantly. Although greater amounts of modern bioenergy, such as liquid biofuels or biomass pellets, have been used in recent years, its growth pace is insufficient to support the requirements of the energy transition. A much stronger and concerted effort is needed, particularly in sectors (shipping, aviation and various industrial applications) for which bioenergy could provide key solutions. Bioenergy will have to be sourced from sustainable and affordable feedstocks, such as agricultural and forestry residues or municipal solid waste.



Annual temperatures in Toronto from 1841-2017
The colour scale goes from 5.5°C (dark blue) to 11.0°C (dark red)

Box 1. IMPORTANCE OF LONG-TERM ENERGY SCENARIOS (LTES) FOR THE CLEAN ENERGY TRANSITION

The world's energy systems are entering profoundly uncharted territory. Unprecedented technological advances in power generation, transport and innovation in digitalisation make predictions about future energy conversion and use highly uncertain.

Users of LTES, namely decision makers in both the public and private domains, are confronted with issues that are complex, interconnected and long-term in nature. While the right choices can bring great economic benefits, poorly informed decisions can result in significant economic costs, including stranded assets, or the failure to employ disruptive innovations to spur faster economic development and meet greenhouse gas emissions targets.

Developers of LTES, are challenged on how to use the available mathematical models and tools to better represent the constant change in the ways electricity is generated, distributed and used, as well as how the whole energy system operates and links with other economic sectors. This is in addition to the challenge of conveying a concise, consistent and clear message that is credible and truly useful for decision makers.

In this context, long-term energy scenarios (LTES) have become an invaluable tool to:

- explore future alternatives to help guide national policy making and to facilitate international debate
- create a coherent view of the growing complexities and interactions among the main drivers of the energy industry
- develop a dynamic, resilient, and comprehensive long-term energy strategy in an uncertain context.

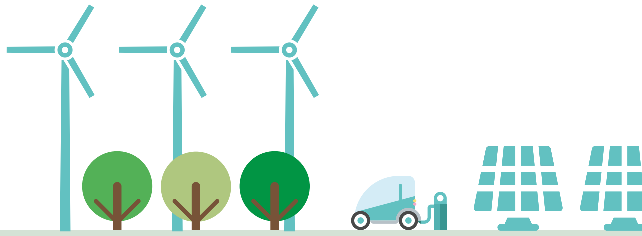
IRENA's new Energy Transition Scenarios Network (ETS-Net) seeks to broaden the understanding and use of LTES as a key tool to support informed government policy decision making, especially in addressing new challenges and opportunities posed by unprecedented energy system transformation. It covers institutional aspects, like who does what and how, as well as technical aspects, such as emerging modelling issues.

The ETS-Net offers participants opportunities to exchange insights on the use and development of LTES through a series of planned activities. Participating countries can learn from others' approaches to scenario use for decision making and gain insights on how to improve their own. It also offers members an opportunity to engage in IRENA's strategic and programmatic work in the field of energy scenario development and planning.

2.2 Transforming, and electrifying, the end-use sectors

The most important synergy of the global energy transformation comes from the combination of increasing low-cost renewable power technologies and the wider adoption of electric technologies for end-use applications in transport and heat. Electrification of end-use sectors utilising renewable power would lead the transition (IRENA 2019f). The renewable energy and electrification synergy alone can provide two-thirds of the emissions reductions needed to set the world on a pathway to meeting the goals of the Paris Agreement.

This section details the key changes that would occur in the main energy-consuming end-use sectors of transport, industry and buildings (residential, commercial and public) over the period to 2050 in the REmap Case.



2.2.1 Transport

KEY FINDINGS:

With accelerated uptake of renewables, the number of light electric vehicles (EVs) on the road could increase to over 1 billion by 2050.

Biofuels would still be important for transport. Total liquid biofuel production would reach 650 billion litres in 2050, and half would be advanced biofuels.

Implications:

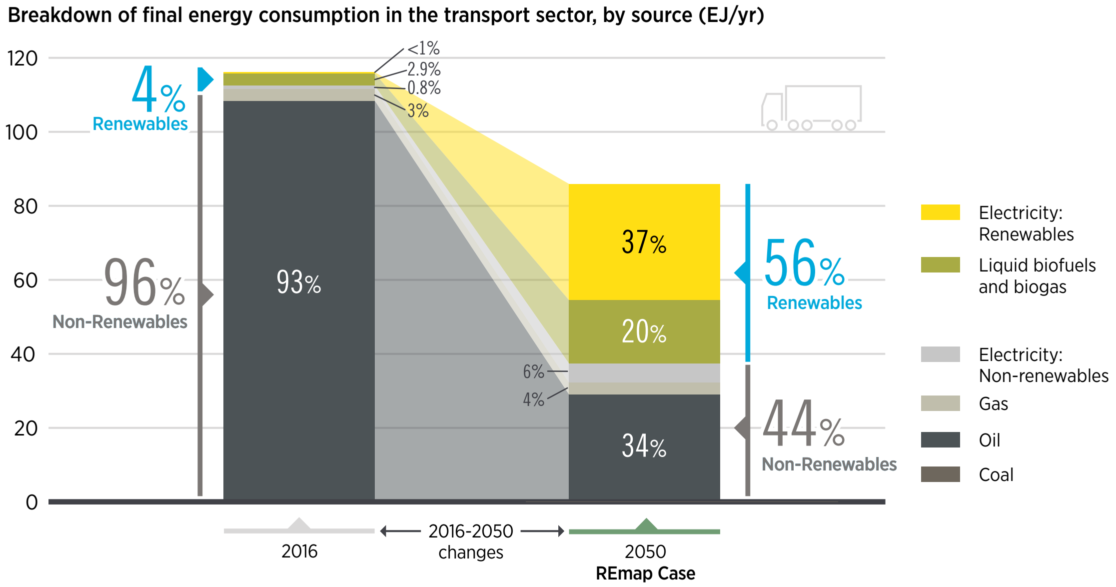
- ***Oblige minimum standards for vehicle emissions.*** Set the priority for electric vehicles for city access.
- ***Accelerate modal shift in transportation.*** Promote the shift from passenger cars to public transport (electric railways or trams), and in the case of freight, move from trucks to electric railways.
- ***Promote electric two- and three-wheelers (e-bikes and electric buses).***
- ***Create the conditions for the electric mobility market to develop.*** Countries could seize the opportunity to learn from first movers who have already implemented mobility targets and to support embracing all types of electric transportation modes, such as passenger vehicles as well as public transport. Captive fleets (like taxis, public cars and delivery trucks) and public transport (including electric buses and vans) could be used as first drivers for the development of the electric mobility solutions and charging infrastructure. Fleet vehicles could also be used to support EV development and promote non-motorised vehicles.
- ***Deploy and incentivise charging infrastructure.*** With a growing number of EVs on the road, charging infrastructure incentives should be designed to kickstart these markets, following already established good practices. Innovative ways of EV charging (e.g. electrified roads) should be promoted.
- ***Promote sector coupling and circular economy.*** During their lifetime, EV batteries can contribute to grid electricity storage capacity and help the integration of higher shares of variable renewable electricity. After their end-of-life, they can be recycled and used as stationary batteries and continue to provide storage capacity.
- ***Support battery and charging research and development (R&D), considering both mobility and grid needs.*** Battery and charging research should be supported to consider the mobility and the grid needs at the same time. In this way, batteries that are already suitable for the grid needs will maintain these capabilities.
- ***Support the standardisation of electric vehicles supply equipment (EVSE).*** Having common standards between EVs and EVSEs, such as charging infrastructure and grid technologies, is essential to ensure their interoperability and to avoid the multiplication of standards. It is a precondition for smart charging to materialise.
- ***Deploy digital technologies for transportation planning and services.*** Transportation needs can be reduced with increased use of advanced digital communication technologies, along with better traffic management and planning. Big data and other digital technologies can improve the optimisation of urban transport planning and displacement services (such as by rerouting to reduce traffic congestion).
- ***Explore innovative mobility services.*** Car sharing, increasing connectivity and autonomous driving can promote energy efficiency and reduce energy consumption through reducing the car fleet and reducing traffic. They also allow better utilisation of resources and connections between different modes, which can help solve the "last mile" problem.
- ***Promote an international biofuels market.*** Liquid biofuels will be fundamental in ensuring deep decarbonisation of transport (see section on Bioenergy for more details). Blending mandates for biofuels should be implemented and increased.
- ***Promote hydrogen as a potential transport fuel.*** Hydrogen can be used in fuel cell electric vehicles (FCEVs), mostly for heavier freight transport but also for some passenger transport.

The transport sector lags behind in the energy transition. Globally, the share of renewable energy in this sector is very small at just 3% in 2016. The use of renewables is dominated by biofuels, mostly bioethanol and biodiesel. Electrification, one of the technologies that can help to decarbonise the sector (if utilising renewable power) is also extremely limited: it currently has a share of just above 1%. Shipping and aviation are entirely fuelled by fossil sources. However, there is significant potential to transform transport. **The REmap analysis shows that a combination of low-carbon approaches would cut transport emissions to just 2.4 Gt CO_2 annually by 2050, which represents almost 80% reduction compared to levels in 2016.**

Under the REmap Case, the transport sector increases the electrification of passenger transport significantly as well as the use of biofuels. The REmap Case also assumes the introduction of hydrogen produced from renewable electricity as a transport fuel. The combination leads to a drop of nearly 70% in oil consumption by 2050 compared to 2016. The share of electricity in all of transport sector energy rises from just above 1% in 2015 to 43% in 2050, and 86% of that electricity would be renewable. Biofuels increase their share from just below 3% to around one-third in the same period.

Figure 10. Increasing electrification in the transport sector

A breakdown of final energy consumption in the transport sector, by source (EJ/yr)

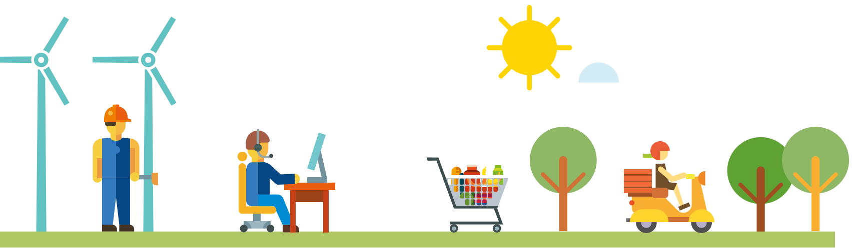


Renewable electricity use could increase significantly in the transport sector by 2050, providing 37% of total transport energy consumption and, due to higher efficiency, covering 60% of the overall transport activity.

Electrification is changing the transport sector. As performance improves and battery costs fall, sales of electric vehicles, electric buses and electric two- and three-wheelers are growing. By the end of 2018, over 5 million light electric cars were on the road (IEA 2018b; INSIDEEVs 2019). Under the REmap Case, the number would increase to over 1 billion by 2050. (That number could double if it includes all types of electric two- and three-wheelers). To achieve this, most of the passenger vehicles sold from about 2040 on would need to be electric. Under the REmap Case, while over half the stock of passenger vehicles would be electric by 2050, closer to 75% of passenger car activity (passenger-kilometres) would be provided by electric vehicles.

Under the REmap Case, total liquid biofuels production grows from 129 billion litres in 2015 to 652 billion litres in 2050. Half would be advanced biofuels, which can be produced from a wider variety of feedstocks than conventional biofuels, but which supply just 1% of biofuels today (IRENA 2016b). The steep increase in biofuels production would require careful planning that fully considers the sustainability of the biomass supply.

Another option that the REmap Case explores is the use of hydrogen as a transport fuel, such as using it in vehicles powered by fuel cells. This option is particularly relevant because variable renewable electricity generation is expanding and the production of hydrogen from renewable power may provide an important option for providing demand flexibility and expanding renewable power generation (IRENA 2018d). Although the technology is not yet ready for widespread commercialisation, some countries believe hydrogen is a potential transport fuel.



Nearly USD 14 trillion of total investment would be required under the REmap Case in the transport sector over the period to 2050. Compared to the Reference Case investments, an additional investment of USD 6 trillion will be needed to deploy REmap options in the transport sector from now until 2050. In addition, around USD 2.0 trillion would be needed to develop the biofuels industry, predominantly advanced biofuels, along with USD 0.5 trillion for hydrogen.

Figure 11. Transport sector key indicators infographic

TRANSPORT

	2016	REmap Case 2050
RENEWABLE ENERGY AND ELECTRIFICATION		
Renewable share in final energy use in transport	3%	56%
Electricity share in final energy use in transport	1%	43%
ELECTRIFICATION		
Electric passenger cars	1.2 million units	1 109 million units
Electric buses and light duty vehicles	0.02 million units	58 million units
Electric 2/3 wheelers	200 million units	2 402 million units
Battery Storage available to grid from EVs[i]	0.5 GWh	14 065 GWh
BIOFUELS		
Ethanol	94 billion litres	366 billion litres
Biodiesel	35 billion litres	180 billion litres
Aviation biofuel	0 billion litres	105 billion litres
Biomethane	0.4 billion m^3	13 billion m^3
ENERGY RELATED CO_2 EMISSIONS	8.5 Gt CO_2/yr	2.4 Gt CO_2/yr
Avoided CO_2 emissions in 2050 compared to Reference Case:		6.1 Gt CO_2/yr
INVESTMENT		
Total investments for decarbonisation over the period 2016-2050		14 USD trillion

i Considering 50% grid connected Electric passenger cars and 25% grid connected electric 2/3 wheelers by 2050

2.2.2 Buildings

KEY FINDINGS:

In the REmap Case, the overall energy consumption of the buildings sector decreases by 15% by 2050 thanks to energy efficiency and electrification of heat. The share of renewables would increase to 81%.

Heat pumps would play a critical role in the buildings sector and would increase to over 250 million units in 2050, supplying 27% of the heat demand.

Buildings will be central to the energy transition by offering opportunities for energy efficiency improvements, by being a site for energy production through distributed energy resources (DER), by providing energy storage to the power system (both with rooftop batteries and with EVs) and by allowing better grid management through electricity demand response.

Implications:

- ***Promote circular economy in buildings and communities, and promote waste to energy solutions.***
- ***Energy efficiency is the key, so it is important to design energy efficiency retrofit financing schemes and to create and promote programmes for retrofitting and renovation.*** It is critical that all new buildings are net-zero emissions. To achieve that they must be designed under the highest energy efficiency standards, deploy super-efficient domestic appliances and be equipped with solar thermal and heat pumps to provide hot water and space heating where needed. In parallel, the renovation and refurbishment of existing buildings must be accelerated. New buildings should be required to meet minimum efficiency and emissions standards. Incentives should be offered for retrofits, and construction municipal codes in cities and states should be adjusted to require higher efficiency.
- ***Digitalisation is a key enabler to amplify the energy transformation.*** Digitalisation through technologies such as smart meters makes it possible to manage large amounts of data, to optimise systems with many small generation units and to manage demand by reducing it when energy is short in supply and shifting it to times when the supply is high. Because buildings are a main component of electricity demand, allowing energy service demand in buildings to better respond to electricity supply will be crucial. Buildings infrastructure should be prepared for higher electrification, including EV charging, battery storage and heat pump installation.
- ***Promote energy management for load flexibility.*** Batteries can be embedded into appliances to contribute to load management. The deployment of smart meters should be accelerated. Smart home technologies and digitalisation can be harnessed to allow better management of energy supply and demand.
- ***Promote distributed energy resources (DER) deployment and improve the regulations for "prosumers".*** The public sector can be involved by encouraging the application of renewable distributed energy resources (DER) (small scale wind, rooftop solar PV) in public buildings. The public sector also can play a crucial role in supporting delivery model innovation through research and pilot projects. Distributed energy resources should be promoted in new public building contracts. Market and regulatory barriers should be removed to foster the deployment of DER, and regulations should be established or improved to allow "prosumers" (those who both produce and consume energy) to take more active roles in systemic innovation.
- ***Promote alternative heating technologies such as heat pumps.*** Heat pumps can achieve energy efficiencies three to five times higher than boilers and can be powered by renewable electricity.
- ***Traditional uses of biomass must be phased out and replaced by efficient and clean cookstoves.*** Traditional uses of biomass are often very inefficient and cause severe indoor air pollution. Efforts should be made to replace those traditional fuels with modern biomass fuels, efficient cookstoves and electric cookstoves.
- ***Plan cities for better connectivity.*** This is vital to promote efficiency in urban services and the development of smart cities.

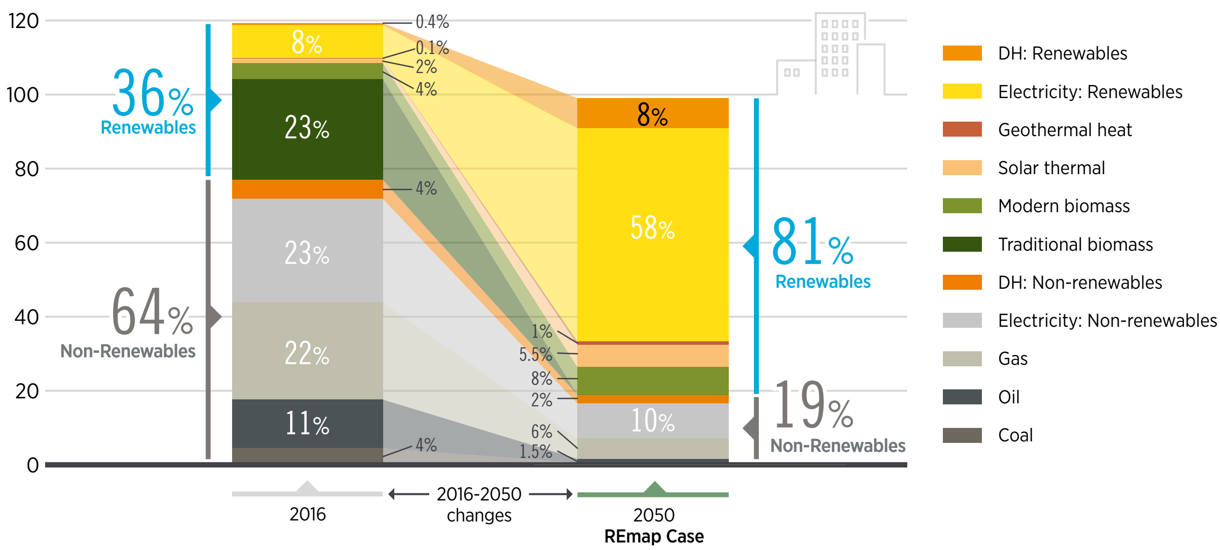
The buildings sector would also contribute to the energy transformation. The buildings sector currently covers a residential and commercial floor area of 144 million square metres (m^2) (Ürge-Vorsatz et al. 2015). This is projected in the Reference Case to increase to nearly 269 million m^2 by 2050. Buildings make a significant contribution to global emissions and need to play a central role in the efforts to reduce those emissions. Although this role is widely recognised, the sector has so far moved slowly to promote the energy transformation. In 2016, 30% of final energy was consumed in buildings, and of that energy around one-third was renewable.

By 2050, the buildings sector would see its overall energy consumption decrease by around 15% in the REmap Case, mainly due to efficiency, especially in cooling, but also due to electrification of heat. The sector will also see its share of renewable energy increase to 81%, up from one-third today, largely due to consuming a large share of renewable electricity.

Figure 12. The increasing use of renewable electricity in buildings and the decline of fossil fuels

Breakdown of final energy consumption in the building sector, by source (EJ/yr)

Breakdown of final energy consumption in the building sector, by source (EJ/yr)



Renewable electricity would reach a 58% share in the buildings sector by 2050. Together with modern biomass, solar thermal and district heating, overall renewables could ramp up to 81%, from 36% today.

Despite the addition of 1 billion new households by 2050, overall buildings energy consumption in 2050 would be only about four-fifths of today's level.

Electricity demand in the building sector is projected to increase by 80% by 2050. The increase occurs despite improvements in appliance efficiency because of strong growth in electricity demand (particularly in emerging economies) and increases in the electrification of heating and cooling. The REmap Case considers deployment of highly efficient appliances, including smart home systems with advanced controls for lighting and air conditioning, improved heating systems and air conditioners, better insulation, replacement of gas boilers by heat pumps and other efficient boilers, and retrofitting of old and new buildings to make them more energy efficient.

In total, around USD 32 trillion would need to be invested in the buildings sector to transform the sector to reflect the REmap Case between now and 2050. Of this, energy efficiency measures would require a cumulative investment of USD 29 trillion over the period to 2050. An additional USD 3 trillion would need to be invested in end-use renewable energy technologies, such as biomass boilers and solar thermal systems and electrification of heat technologies such as heat pumps.

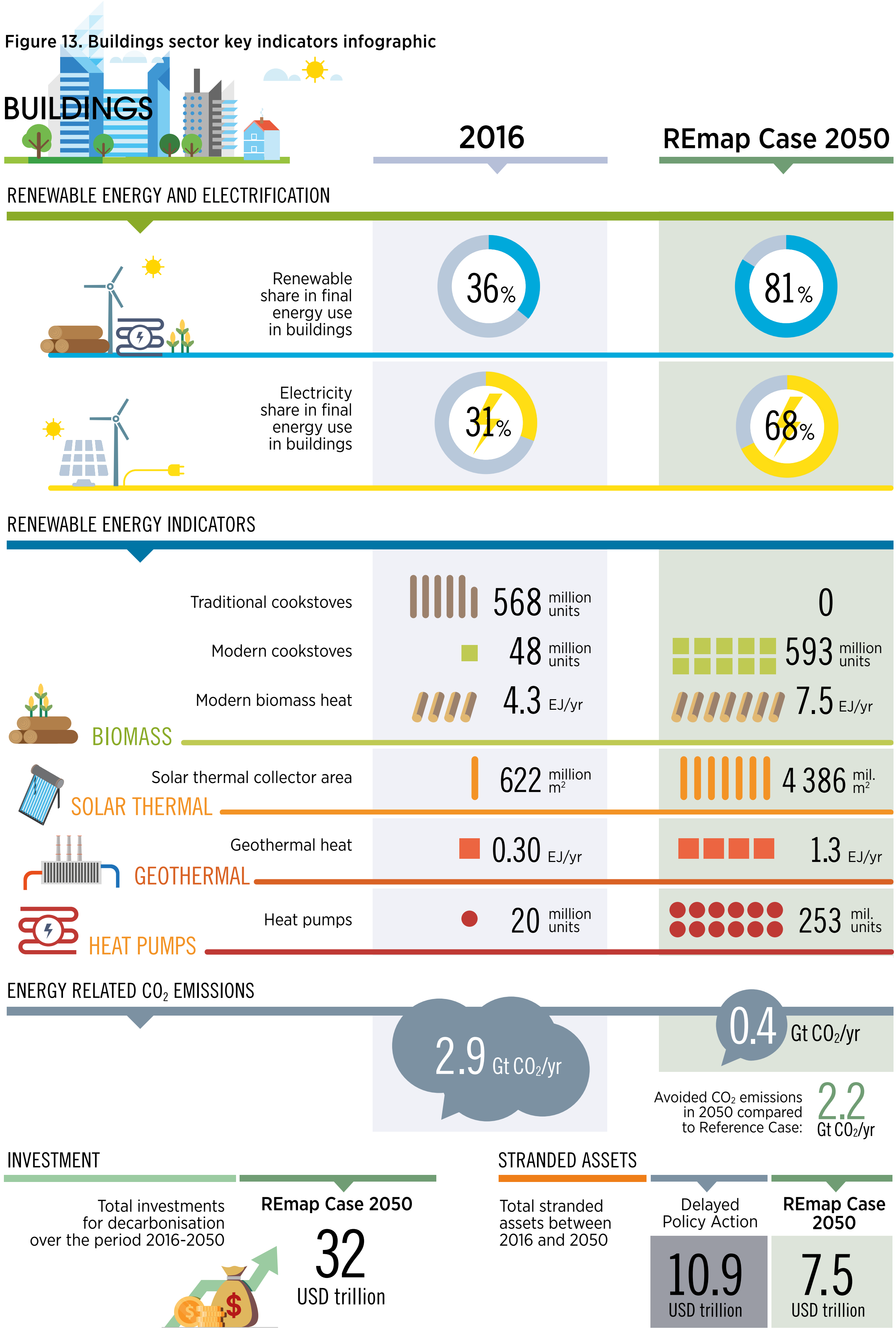
The share of modern renewables (excluding traditional uses of biomass) for heat and other direct uses would grow substantially. The largest increase is in solar thermal systems, which would increase total heater area six-fold, from around 600 million m^2 to over 4 000 million m^2.

Heat pumps are also poised to play a critical role. Heat pumps achieve energy efficiencies three to five times higher than fossil-fuelled boilers and can be powered by renewable electricity. Under the REmap Case, the number of heat pump units in operation would increase from around 20 million in 2016 to around 253 million units in 2050. They would supply 27% of the heat demand in the buildings sector. Efficient and clean district energy systems would provide 16% of buildings heat demand, more than double today's level.

The shift in cooking technologies from fuel combustion to electricity would also promote renewables, due to the high share of renewable power in the electricity supply. Electric stoves, such as induction cookstoves, can cut the energy demand of cooking by three to five times. In addition, more renewable-based stoves that use modern biofuels and solar energy could be deployed.

New as well as renovated buildings can be made more energy efficient and rely largely on renewable technology to supply their remaining energy demand. The majority of efficiency investments (88% under the REmap Case) will be spent on making buildings more energy efficient. Early action is required to avoid stranded assets and meet future reinvestment needs.

Figure 13. Buildings sector key indicators infographic



2.2.3 Industry

KEY FINDINGS:

Under the REmap Case, industry would increase its share of renewable energy to 62%, and renewable electricity would meet 42% of the sector's energy needs by 2050.

By 2050, the industry's use of solar thermal heat will rise steeply and provide 4% of industry's heat demand.

For low-temperature heat needs, heat pump installations would also increase to 80 million, while for medium- and high-temperature processes, bioenergy would still remain critical.

Implications:

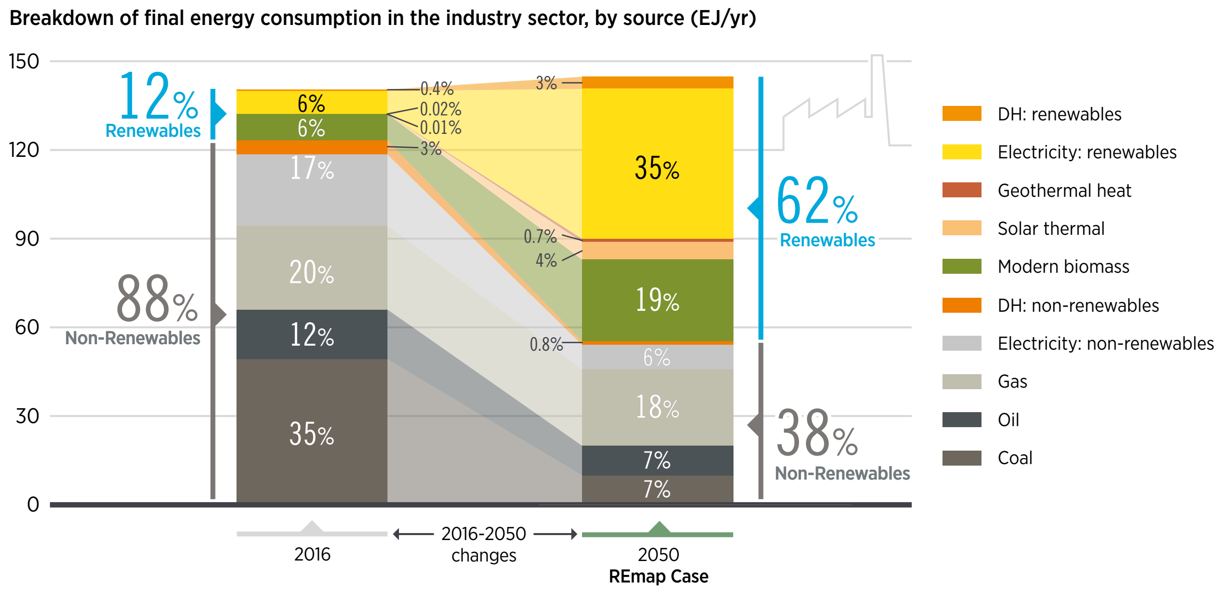
- ***Strengthen the circular economy.*** The circular economy would include reusing, recycling and reducing the use of materials and feedstocks all of which will improve energy efficiency. It also includes cogeneration, industrial district management and waste heat recovery.
- ***Consider moving energy-intensive industries to countries with higher resources and shares of renewables.***
- ***Incentivise (e.g. through prices or taxes) energy efficiency and renewables investment from industries.***
- ***Promote corporate sourcing and self-generation of renewable electricity.*** In many countries, the conditions are not in place that allow industry to rely on self-generation or sourcing outside of the regulated market. Policy and regulation thus should allow for more flexibility if the electricity supply is from renewables and recognise the benefits of moving away from fossil-based electricity generation.
- ***Promote distributed renewable energy deployment and improve regulations for prosumers.*** Allowing and promoting distributed energy resources on site would enable industrial consumers to also produce energy (making them into prosumers) and to participate in ancillary services. Large consumers should take an active role in energy management services.
- ***Keep a strong focus on energy efficiency by making processes ever more efficient and by setting or mandating minimum standards on energy efficiency and/or on the carbon intensity of fuels, processes and products.***
- ***Develop sustainable bioenergy supply chains to meet the growing need for bioenergy in industry to supply heat demand, especially high-temperature heat.***
- ***Promote alternative heating technologies.*** These include solar thermal units, heat pumps and geothermal resources, especially for low- and medium-temperature applications.
- ***Integrate hydrogen from renewables in industrial processes.*** Hydrogen produced from fossil fuels, currently widely used in several industry sectors (refineries, ammonia, bulk chemicals, steel, etc.), can be replaced by hydrogen produced from renewables. Hydrogen from renewables could also replace some fossil fuel-based feedstocks in these CO_2 emissions-intensive applications.

In terms of emissions, industry is the second-largest emitter of energy-related CO_2, after the power sector, and is responsible for a little under one-third of these emissions worldwide (when including process emissions). But in 2016, renewables provided only around 14% of the industry sector's energy demand, and most of this was bioenergy. Electricity supplied 23% of the energy consumed by the sector. The REmap Case reduces the sector's emissions by 60% by 2050. Industry would still emit more than 3 Gt of CO_2 in 2050, and industry would become the largest source of emissions. Within the sector, chemical, petrochemical and steel are among the largest emitters, because they employ energy-intensive and high- temperature processes that are difficult to decarbonise. To achieve the level of decarbonisation proposed under the REmap analysis, investment in low-carbon energy technologies in industry would have to increase significantly. Total investments during the period to 2050 would amount to USD 6.1 trillion.

Under the REmap Case, industry would increase its share of renewable energy to 63% by 2050. Under the energy transition, electricity would meet more than 40% of industry's energy needs by 2050. While renewable electricity would become the largest source of renewable energy consumed in the sector, bioenergy sources would remain the largest source of renewable heat by a large margin and would be based largely based on residues used for direct heat and combined heat and power (CHP).

Figure 14. Renewable electrification and bioenergy taking the lead in the industry sector

Breakdown of final energy consumption in the industry sector, by source (EJ/yr)



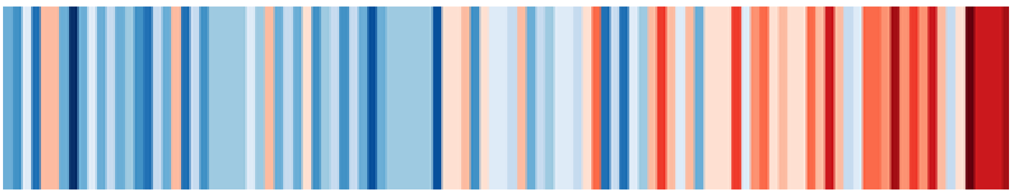
By 2050 the share of renewables in the industrial sector needs to grow by more than five times. Renewable electrification wouldmake up around one-third of the sector's energy demand, followed by biomass providing one-fifth.

In percentage terms, the largest growth would be in the use of solar thermal heat for low-temperature processes. Under the REmap Case, industry's use of solar thermal heat will rise steeply to reach 2.4 billion m2 of solar thermal collectors (concentrated and flat plate) by 2050, providing 4% of industry's heat demand. By 2050, 80 million heat pumps would also be installed to meet similar low-temperature heat needs, more than 80 times the number in use today.

For medium- and high-temperature processes, bioenergy would remain critical. Its use would triple in absolute terms. Biomass could also be used as a feedstock for petrochemicals. Bioenergy will be drawn from biomass residues and industry waste. To realise the potential of biomass, industry will need to scale up the use and collection of residues and develop efficient supply chains for their sale and distribution.

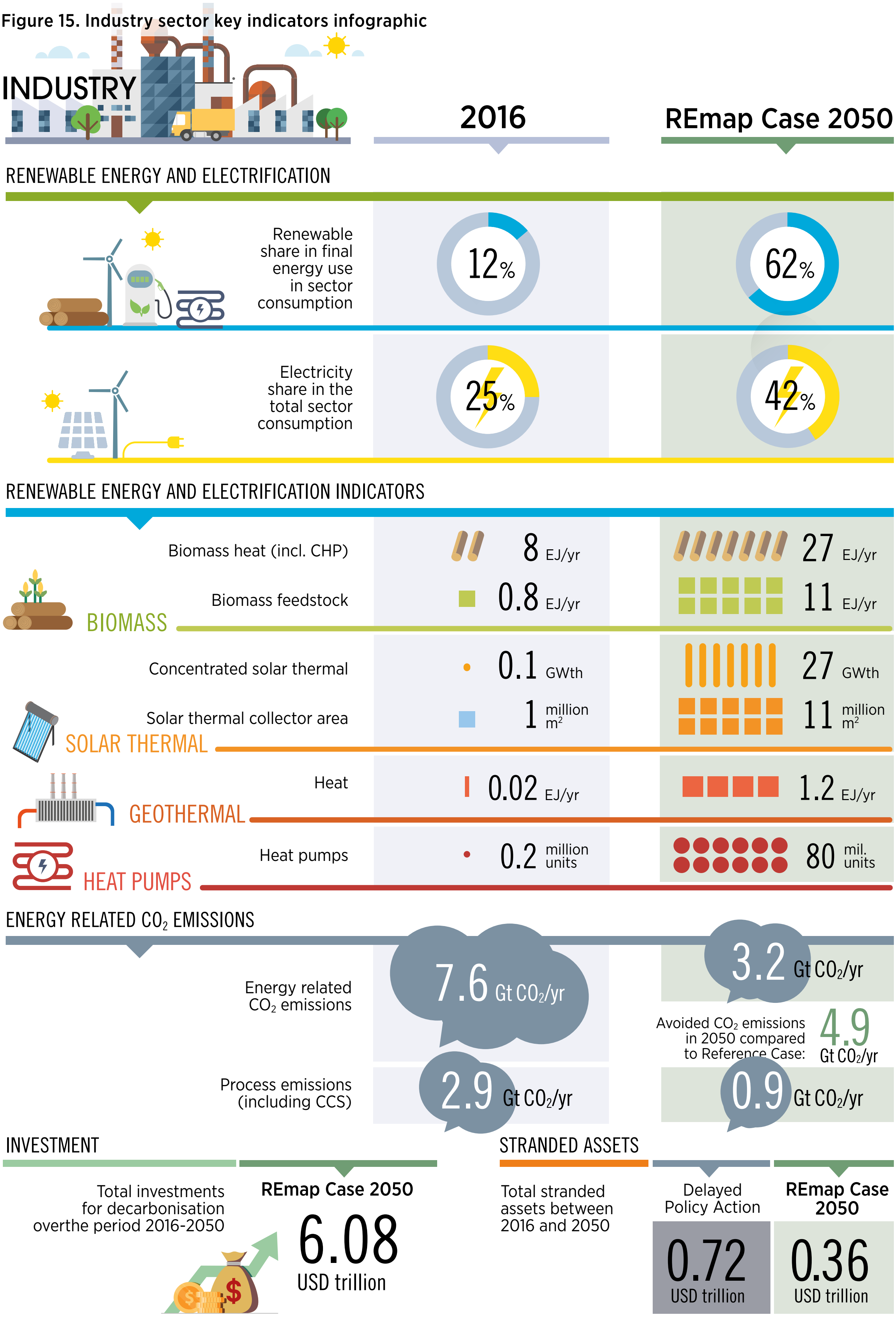
Hydrogen would also play an important role in the sector: the use of hydrogen derived from renewables grows to over 14 EJ by 2050. In industry, hydrogen will principally be used to replace natural gas and as a feedstock to produce chemicals and other products (IRENA 2018d).

There is a large potential to improve efficiency in the industrial sector. Global industrial energy consumption could be reduced by about a quarter if the best available technologies were adopted. Most of the improvements can be made in developing countries and economies in transition. In particular, the sector can improve its process efficiency, adopt demand side management solutions, introduce highly efficient motors, develop material recycling and strengthen waste management.



Annual temperatures for Australia (1910-2017)
The colour scale goes from 20.7°C (dark blue) to 23.0°C (dark red)

Figure 15. Industry sector key indicators infographic



2.3 Decarbonising the world's energy supply

As the renewable energy share of primary energy increases from 14% today to 65% in 2050, significant changes would need to take place in how the world sources its energy. Fossil fuel consumption would continuously decline from 2020 onwards. Demand for fossil fuels would decline by 21% by 2030, and by 66% by 2050, in part through the increasing use of renewable electricity. This increasingly electric energy system would bring a major transformation in how the supply sectors and demand sectors interact.

This chapter goes into depth on the key changes that are needed in the energy supply. It focuses on deep and transformational changes to the power system that have not been seen since the advent of the modern electrical grid. It also explores some of the complementary solutions that will be required, including hydrogen and biofuels.

2.3.1 Power

KEY FINDINGS:

The power sector would need to undergo a deep decarbonisation, reaching an 86% renewable energy share in electricity generation, up from an estimated 26% in 2018.

The largest technology deployment is for solar PV, with 8 500 GW, and wind, reaching 6 000 GW in 2050. Total investments in renewable generation capacity over the period total USD 23 trillion.

Implications

- ***Promote systemic innovation that brings together digitalisation, decentralisation and electrification in the energy sector.*** As these three innovation trends expand into the energy sector, they are changing the roles and responsibilities of actors and unlocking system flexibility for a high share of variable renewable energy (VRE) penetration.
- ***Build no new coal power plants and accelerate the decommissioning of existing coal capacity.***
- ***Identify and map renewable energy resources and develop a portfolio of financeable projects over the medium and long terms.*** Market-based instruments to contract renewable energy projects should be promoted.
- ***Highly flexible power systems are needed to accommodate the variability of solar and wind power generation and the new patterns of decentralised electricity generation and consumption.*** High levels of electrification coupled with decentralised energy sources require a high level of technical flexibility (through flexible supply, transmission, distribution, storage, demand response, power-to-X, electric vehicles, etc.) complemented by operational flexibility.
- ***Conventional thermal generators have to become more flexible.*** Retrofitting physical components and making operational modifications can increase flexibility by achieving lower minimum load, shorter start-up times and higher ramp rates. These upgrades could also benefit the profitability of conventional generators.
- ***Adjust regulations to increase space and time granularity of system operation and pricing.*** This makes it possible to better capture the characteristics of VRE and to provide better market signals for generators and consumers.

- ***Revise tariff structures and price regulations.*** Regulations needs to be adjusted to reflect the true electricity costs of different consumers. They also need to avoid cross-sectorial subsidies and to internalise carbon pricing.
- ***Adapt regulations and aid in the development of an active market to allow energy consumers to participate in ancillary service markets.***
- ***Implement new regulations to provide the flexibility that the system needs.*** Better market signals are needed to enable flexibility resources to come into play to cope with the uncertainty and variability of VRE generation. Examples include real-time variable pricing and shorter trading intervals.
- ***Traditional power system operations need to adjust for prosumers and digitalisation.*** The ability of end users to also produce energy (i.e. being prosumers), along with new business models, digitalisation, increased connectivity, smart appliances, internet of things and storage, will allow better use of grids and assets to manage daily loads and the seasonality of supply and demand.
- ***Remove barriers for decentralised energy resources.*** Decentralised energy resources (such as vehicle-to-grid (V2G), distributed generation, stationary batteries, virtual power plants) should be fostered, while users should be allowed to take active roles as prosumers.
- ***Fluctuating demand is important as a source of flexibility.*** Hydrogen, electric vehicles and heat pumps are among the key enablers for a more flexible demand that can provide storage at all time scales for VRE integration (storage from EVs for hours, heat for days and hydrogen up to seasonal).
- ***Systemic innovation is needed to unlock investments in renewable energy capacity, particularly VRE.*** Investments will take place only if investors can make reasonable profits. That requires systemic innovation on policies, market design and regulatory frameworks to allow renewable energy to become the main energy product in the market and to avoid curtailment.
- ***Technology innovations are needed to facilitate the integration of VRE into power systems.*** This is a necessary condition that should be put in place for the energy transition to be cheaper than the Reference Case (or the business-as-usual case), providing a net benefit.
- ***The remaining hydropower potential should be developed and optimally operated.*** That will facilitate the integration of VRE.
- ***Explore relevant applications and benefits of technology advances for operations and commercialization.*** These include artificial intelligence and blockchain, which also facilitate the management of decentralised resources.
- ***New grid developments can foster the deployment of renewables.*** Microgrids based on renewables help increase electricity access in regions like Africa, while super grids can interconnect large countries, regions or even continents, allowing the complementarity of resources and helping the balancing of the systems.
- ***Promote aggregators.*** This new role should be encouraged. Aggregators can provide multiple services to the system and offer new opportunities, while also helping to promote renewables and energy efficiency.
- ***Planners, regulators and operators must develop new skills and competences.*** They should foster and adjust policies, regulations and codes to integrate the innovations that are needed to transform the energy system.
- ***Update the grid codes.*** Grid codes need to be revised to better integrate rising shares of variable renewable sources (mainly solar PV and wind).
- ***Adjust regulation to allow a market for renewably-produced hydrogen to benefit from low electricity prices.***

Delivering the energy transition at the pace and scale needed would require the almost complete decarbonisation of the electricity sector by 2050. This can largely be achieved by using renewables, increasing energy efficiency and making power systems more flexible. Under the REmap Case, electricity consumption in end-use sectors would increase 130% by 2050, to over 55 000 TWh, compared to 2016. By 2050, the share of renewable energy in generation would be 86%, up from an estimated 26% in 2018. Meanwhile, the carbon intensity of electricity generation would decline by 90%. Variable renewable energy, mainly wind and solar PV, would reach 60% of generation. These sources would lead the way for the transformation of the sector, rising from around 514 GW of wind capacity and 385 GW of solar PV in 2017 to over 6 000 GW and 8 500 GW by 2050, respectively. In addition, strong growth in geothermal, bioenergy and hydropower would be seen as well.

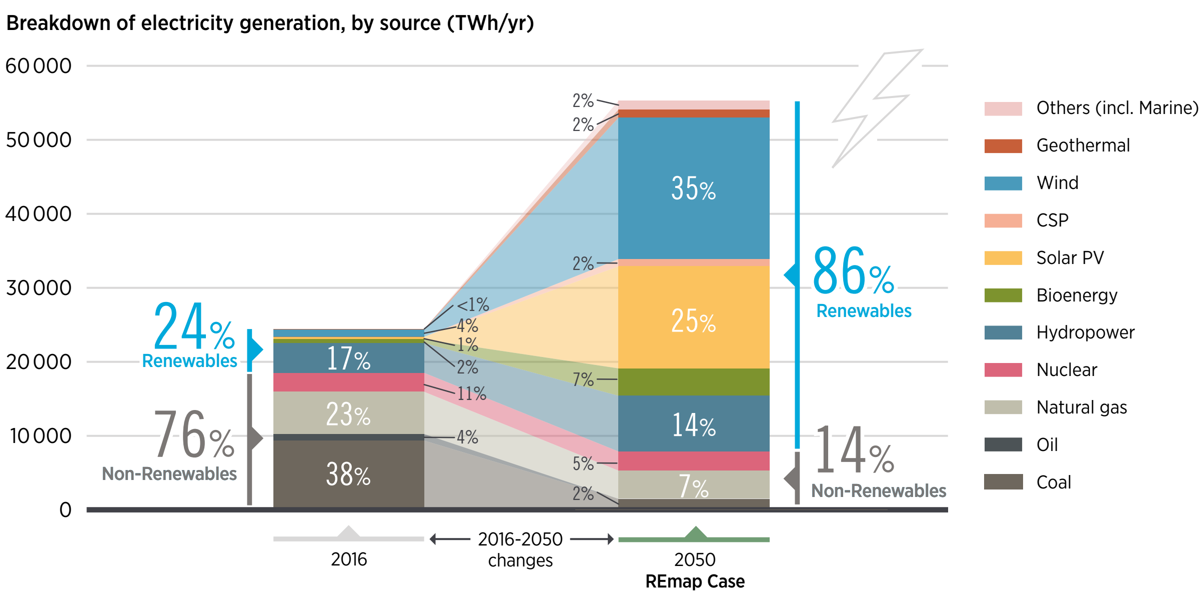
Annual additions of renewable power capacity would exceed 600 GW per year, 84% of which will be from solar and wind technologies. Decentralised renewable power generation grows from just 2% of total generation today to around one-quarter by 2050, more than a ten-fold increase.

Investment in new renewable power capacity would increase to over USD 650 billion per year over the period to 2050. Transforming the power system to produce around an 86% share for renewable power would require investments in infrastructure and energy flexibility of another USD 350 billion per year (a total of USD 12 trillion for the period 2016-2050). In all, investment in decarbonisation of the power system will need to reach an average of nearly USD 1 trillion per year to 2050.

Over the period between 2016 and 2050, investments in renewable power generation capacity would total USD 23 trillion in the REmap Case, more than double the investment requirements in the Reference Case of USD 11 trillion. Three-fourths of the additional investments are required to deploy variable renewables, mainly wind and solar PV.

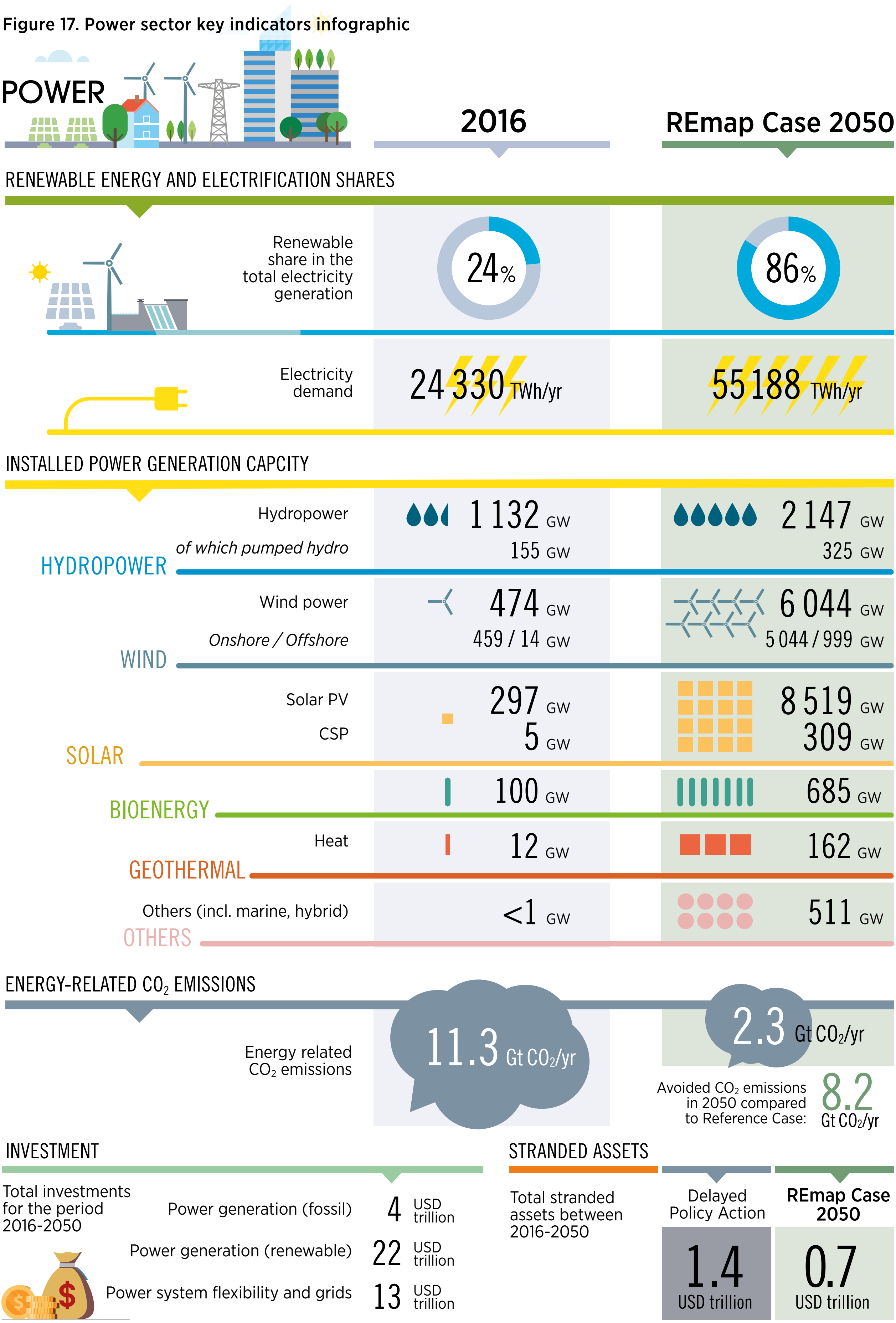
Figure 16. The rising importance of solar and wind energy in the power sector

Breakdown of electricity generation by source (TWh/yr)



Gross power generation would almost double, with 86% coming from renewables and 60% specifically from solar PV and wind power.

Figure 17. Power sector key indicators infographic



Box 2. INNOVATION IN THE POWER SYSTEM TO COPE WITH HIGH SHARES OF VARIABLE RENEWABLE ENERGY

The world's energy system is in the midst of a technology driven transformation towards a more inclusive, secure, cost-effective and low-carbon sector. The REmap analysis concludes that accelerating the energy transition requires far more than a societal and market transformation, it also requires deep technological changes in the supply and demand side. Innovation is the engine powering the energy transformation and is needed across the whole energy system to assist in the integration of variable renewable energy (VRE) technologies. While the power sector has been leading the way with rapid cost reductions in the key renewable energy technologies of solar and wind, new solutions are being tested in a wide range of countries to increase the flexibility of the system and enable high levels of VRE integration.

The REmap analysis shows that in 2050, the global share of VRE would rise to 60%. However, higher shares could be found in some regions, such as North America (75%) and East Asia (73%), as well as countries such as Germany (74%) and the United States (79%). With such rising shares of VRE in electricity generation, maintaining the balance between supply and demand in a cost-effective manner becomes challenging. Maximising the value of low-cost but variable renewable energy sources requires more flexible and integrated power systems. Innovation efforts are therefore focused on fostering the development and deployment of solutions that create the needed flexibility and that can also electrify the end-use sectors of transport, buildings and industry.

Innovations now being tested show that power systems can operate with very high shares of VRE in a reliable and economical way. However, there is a large gap between the front runners and the majority of followers in integrating VRE. To bridge the gap, the following recommended actions could be implemented by countries that want to maximise the benefits of renewable energy for their economies (IRENA 2019b):

1) **Develop far-sighted policy frameworks and anticipate future power system needs.** Ensuring cost-effective integration of VRE at scale requires balancing present with future needs. Policy makers need to look ahead to a time when renewable energy deployment will be successful and design the markets and systems around this future.

2) **Adopt a systemic approach, as solutions come from combining innovations in technology, markets, business and operations.** Leveraging synergies among innovations across all sectors and components of the system, and involving all actors, is crucial to unlock flexibility across the whole power sector.

3) **Foster learning by doing.** We cannot predict the precise configuration of the best power system of the future. This makes learning by doing, through trial and demonstration, of paramount importance to mitigate risk.

4) **Account for the changing roles and responsibilities of actors required for a successful transition.** New market players will emerge from the increasing penetration of decentralised energy resources. Governments and companies thus need to gather better insights into consumers' and communities' needs and expectations and their willingness to adopt innovations – and should tailor solutions accordingly.

5) **Make market design innovation a priority, as it can foster flexibility at low implementation cost.** Market design solutions for VRE have been shown to have large impacts and low costs. They should be the first option to focus efforts on. Proper planning that accounts for the energy transformation would result in holistic and cost-effective market designs.

6) **Couple the electricity and end-use sectors.** Valuable synergies exist between renewable power and the decarbonisation of end-use sectors. So electrification strategies must be planned carefully and with consideration of wider societal changes.

7) **Turn smart innovations into smart solutions using digital technologies.** Digital innovations (such as artificial intelligence, the Internet of Things, blockchain, etc.) are starting to significantly impact power systems in many different ways. Energy systems should make far more use of the "smartness" that digital innovations enable.

8) **Adopt an open and co-operative approach to innovation.** Innovation needs to engage different actors across developed and developing countries, and knowledge and experience should be shared more widely.

2.3.2 Hydrogen

KEY FINDINGS:

Hydrogen can be produced using remotely located renewable resources, then shipped to centres of high demand to enhance decarbonisation. Regional or global trade involving hydrogen would both increase energy security and improve air quality.

Uncertainties remain about applications for hydrogen. Asian markets seem to welcome hydrogen use mostly in transport, while stationary applications are being considered elsewhere.

Currently, fossil fuel-based hydrogen is cheaper than renewably-produced hydrogen, but green hydrogen is on a solid path to become an economic choice in the future, coupled with low-cost renewable power.

The existing gas grid infrastructure can serve to store and supply renewably-sourced hydrogen.

Implications

- ***Set up a stable and supportive policy framework.*** To achieve rapid scale-up, a comprehensive set of policies would be needed to encourage the appropriate private investments in hydrogen across the entire supply chain (equipment manufacturers, infrastructure operators, vehicle manufacturers, etc.), including in R&D facilities.
- ***Adopt specific instruments to de-risk infrastructure investment and improve the economics of the supply chain.***
- ***Promote certification of hydrogen from renewable power.*** Upstream, the full exploitation of renewable generation capacity for hydrogen production could be facilitated through certification schemes, as they would help to register power use and further highlight the systemic added value of electrolysers.

Electricity from renewables already accounts for a quarter of global power generation. However, as highlighted by the REmap analysis, renewables have the potential to supply 86% of electricity by 2050, which would include channelling large amounts of renewable power into industry, transport and buildings. Direct electrification in these sectors can be challenging for certain uses, however, unless renewable-based power can be further converted and stored via other energy carriers.

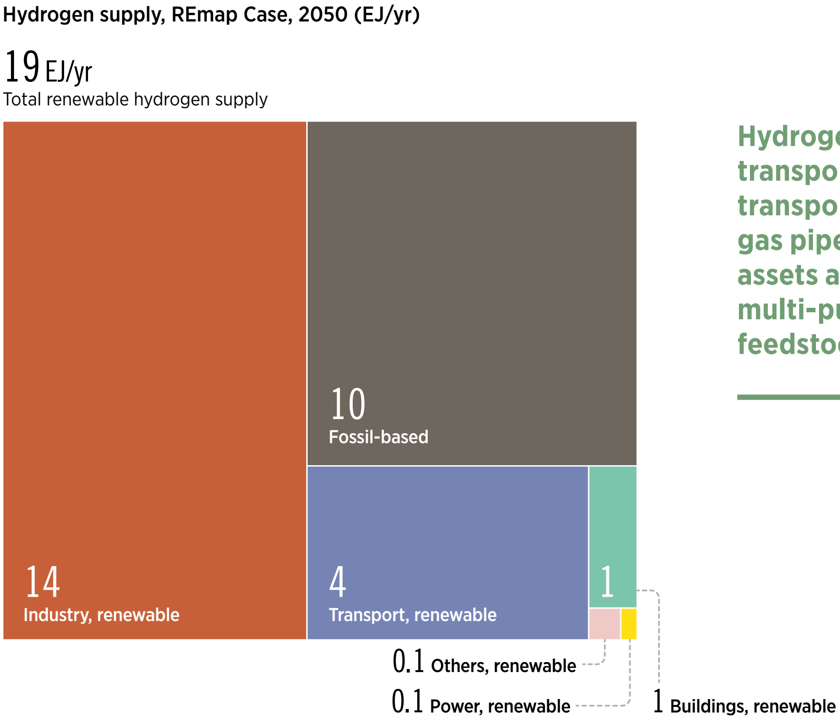
One such promising energy carrier is hydrogen (IRENA 2018d). Historically, it has been produced predominantly from fossil fuels, roughly half of it coming from steam methane reforming (SMR) of natural gas. Oil and coal gasification are also widely used, particularly in Australia and China. Electrolysis currently comprises a small production share of around 4%, mainly as an output of chlor-alkali processes to produce chlorine and sodium hydroxide.

The production of hydrogen by splitting water into hydrogen and oxygen using electricity could be significantly increased. **As an energy carrier, hydrogen made from renewables could be seen as complementary to electricity since it offers a way to transport renewable energy over long distances.** It has the technical potential to channel renewable electricity to subsectors in which decarbonisation is otherwise difficult. Hydrogen for power generation could also play a role in niche applications, such as in remote locations or contributing to generation adequacy, though the efficiency of converting from electricity to hydrogen and back to electricity is low. In summary, hydrogen produced by electrolysers from renewable electricity can directly displace "grey" hydrogen produced from fossil fuels as well as replace fossil fuel-based feedstocks in several industrial processes.

The REmap Case shows that by 2050 hydrogen has the potential to supply nearly 29 EJ of global energy demand, two-thirds of which would come from renewable sources.

Figure 18. Hydrogen can be produced by renewable electricity and play a role in reducing fossil fuel use

Hydrogen supply in 2050 by source of production (EJ/yr)



Hydrogen can be used in the industry, transport and buildings sectors transported through existing natural gas pipelines. It offers a way to recycle assets and transport a renewable, multi-purpose energy carrier and feedstock over long distances.

Today, hydrogen is already employed in the **industry sector**. There is great potential to reduce emissions in chemicals, refining and iron and steel using renewably-produced hydrogen to replace fossil fuel-based feedstocks and to provide high-temperature heat. In the REmap Case, just under 14 EJ of renewable hydrogen would be consumed in industry in 2050, largely in the iron and steel subsectors, and also for ammonia production.

In the **transport sector**, hydrogen can be used in fuel cell electric vehicles (FCEVs), mostly for heavier freight transport but also for some passenger transport. The transport sector would be the second largest user of renewable hydrogen (after the industry sector) at around 4 EJ per year by 2050.

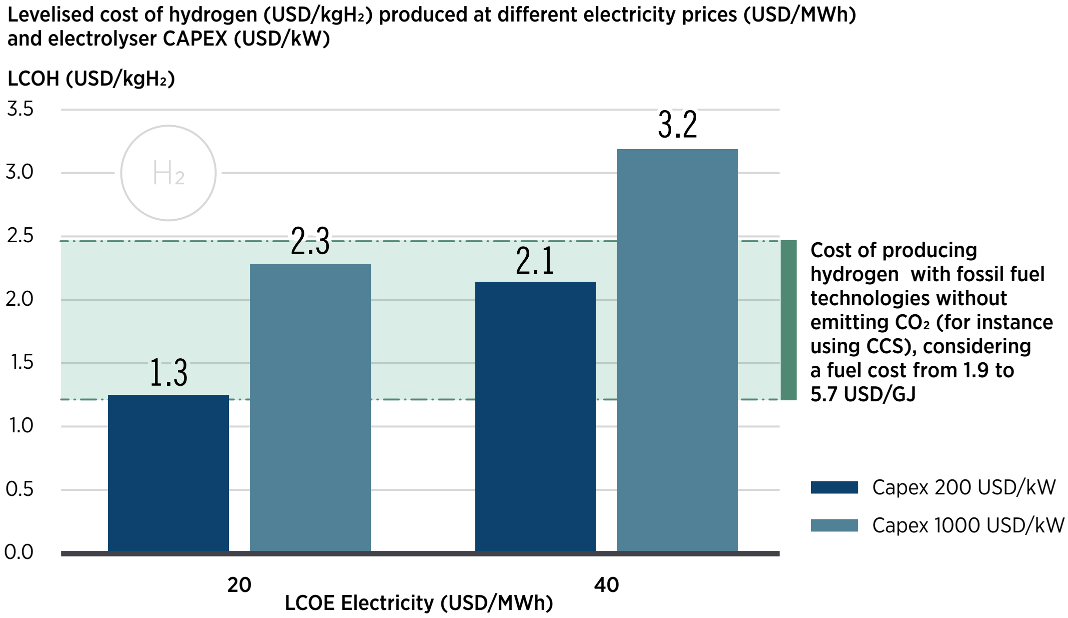
In the **buildings sector**, hydrogen can be blended with natural gas or combined to produce synthetic methane and injected in gas grids. The gas grid in this scenario would function as an existing large-scale storage asset, accommodating and distributing low-cost renewable electricity.

While the opportunities and technologies for producing hydrogen exist, technology development policies have to focus on scaling up production to make hydrogen from renewable power competitive in the market. The challenge is how to make hydrogen economically viable, financially attractive and socially beneficial.

The levelised cost of hydrogen (LCOH) (USD/KgH_2) from renewables is directly proportional to electrolyser load factors, although some electrolysers, according to (Kopp and et al. 2017), reach maximum efficiency at lower loads (about 20% of nominal capacity). Current investment costs (alkaline) reside at around USD 1 000/kW but may decrease in the long term to USD 200/kW if the market increases in size. LCOH from low-cost natural gas available in industry (USD 5/GJ) is currently cheaper than hydrogen from nearly any renewable source today. However, average (USD 10/GJ) to high (USD 16/GJ) natural gas prices for non-household sectors in Europe would make hydrogen from renewables competitive for electricity even today, with

Figure 19. There is room for competitive development of hydrogen produced with renewable electricity

Levelised cost of hydrogen (USD/kgH2) produced at different electricity prices (USD/GJ) and electrolyser CAPEX (USD/kW)

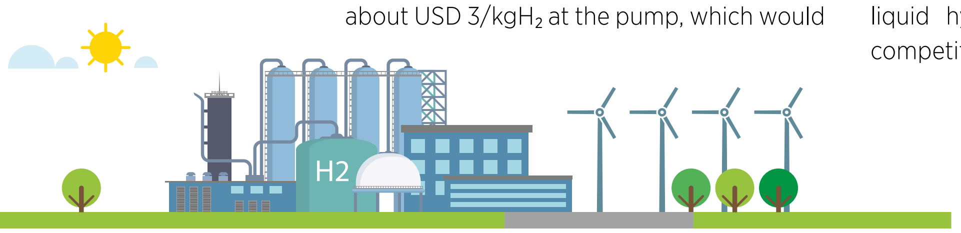


Hydrogen produced from electricity can be competitive if the price of electricity falls to below USD 30/MWh or if electrolyser costs decline significantly.

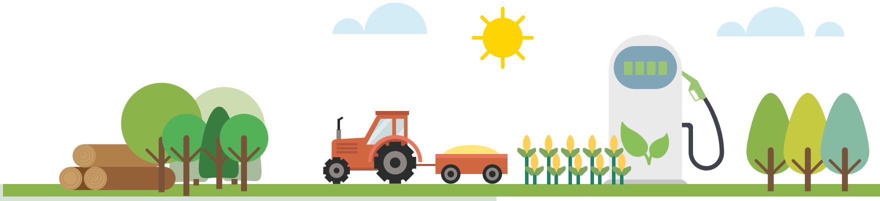
prices below USD 35-50/MWh (about USD 10-14/GJ) running near full load hours per year (Figure 14). Such a high load factor is not likely to occur at present, but gives an idea of the competitiveness that hydrogen from renewables could achieve in the medium term (IRENA 2018d).

To achieve a target cost at the pump of USD 4-6/kgH$_2$ (US and EU), hydrogen production costs would need to not be higher than USD 3/kgH$_2$. Currently, this can be achieved by SMR with carbon capture and storage (CCS) for natural gas with prices of around USD 11/GJ or by alkaline electrolysers (Capex: USD 450/kW) from a renewable electricity price of around USD 40/MWh. Nevertheless, Japan envisions a target of about USD 3/kgH$_2$ at the pump, which would require considerably lower electricity prices (IRENA 2018d).

To date, pipelines are the most economical way to transport hydrogen in large volumes. Existing assets could provide the economies of scale necessary to reduce the cost of hydrogen (IRENA 2018d). Injections in gas grids could also allow continuous operation of electrolysers and could provide a seasonal storage option. For long distances, hydrogen carriers such as liquid organic hydrogen carriers or ammonia are more suitable than gaseous or liquid hydrogen. These have high hydrogen storage densities and can be produced at scale using established industrial processes. However, the cost reduction potential for liquid hydrogen might lead to increased competitiveness.



2.3.3 Bioenergy



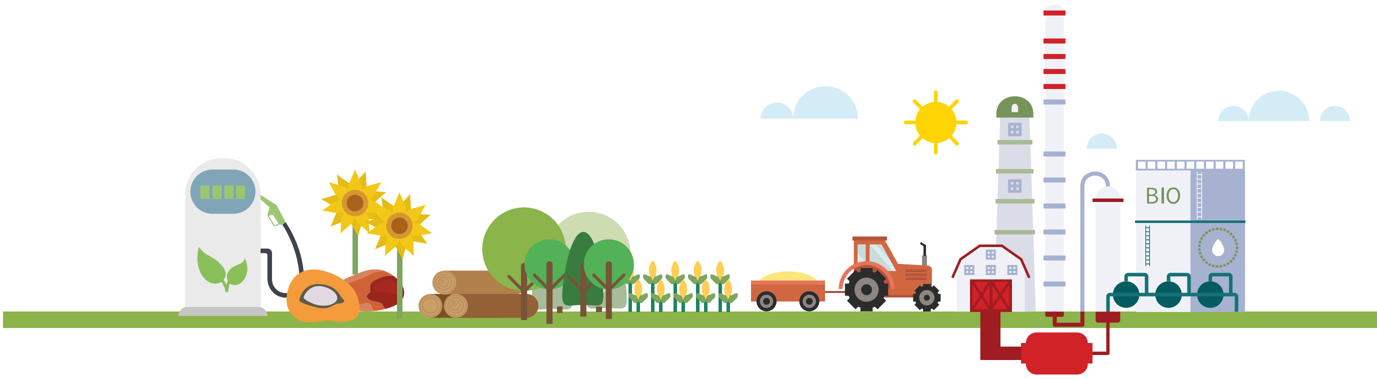
KEY FINDINGS:

Biofuels are important for decarbonising parts of the global energy sector such as in some transport modes, like aviation, and in industry both for process heat and feedstocks.

Bioenergy is the largest form of renewable energy in use today and will remain a significant source of fuel for power and heat generation in industry and electricity production.

Implications

- ***Produce bioenergy in ways that are environmentally, socially and economically sustainable.*** There is a very large potential to produce bioenergy cost effectively on existing farmland and grassland, without encroaching upon rainforests, and in surplus to growing food requirements.
- ***Biomass-based industries – such as pulp and paper, lumber and timber, and food and biofuels – that generate readily available biomass residues are fundamental in the transition.*** Countries should strive to make the best use of these resources.
- ***In sectors such as aviation, shipping and long-haul road transport, biofuels might be the main or only option for decarbonisation for years to come.*** Targeted attention and specific policies must be devoted to these sectors and to the development of related biofuels supply chains, including a strong focus on research, development and deployment of technologies that make the best use of biomass resources.
- ***Increase trade on biofuels to minimise sustainability risks.*** Very often the potential supply of sustainably-produced biofuels is not located where the demand for those biofuels is. It is important to remove barriers and promote trade of sustainably-produced biofuels so that costs are reduced and sustainability risks are mitigated.
- ***Emphasise blending mandates to create reliable, long-term demand for biofuels.*** Additional policies that recognise the carbon benefits of sustainably-produced biofuels should be considered. Adding an economic incentive to their production would ensure that positive externalities are reflected in market decisions.

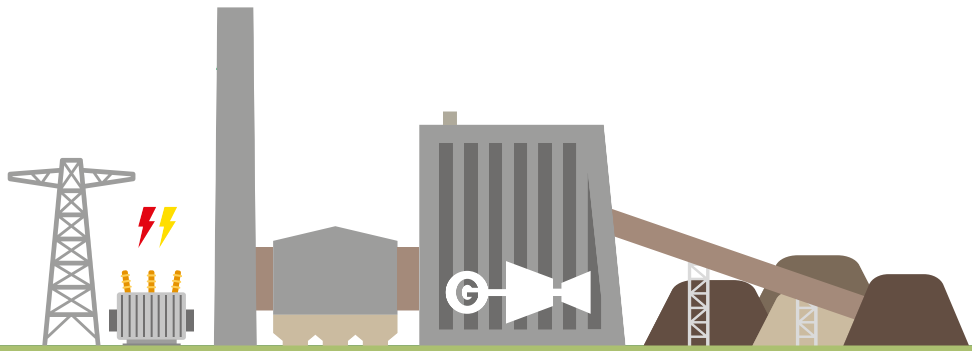


Bioenergy is the largest form of renewable energy in use today, globally accounting for more than 75% of the renewable energy supply and 5% of total primary energy supplied. About a quarter of the bioenergy is used in the transport sector, mostly in the form of liquid biofuels from crops like sugarcane and maize. The rest is used for cooking, heating and power, through combustion of feedstocks like wood and straw.

Cooking with biomass is largely done outside of the modern energy sector in developing countries. Inefficient traditional cookstoves emit indoor smoke that imperils the health of women and children. Much of the wood fuel they use is collected on an unsustainable basis from local forests. They must be replaced with clean and efficient modern cookstoves, which must be fuelled with sustainably produced wood or ethanol. There is excellent potential for farmers to raise wood in an agroforestry approach in which nitrogen-fixing wood crops naturally fertilise food crops planted alongside them (IRENA 2019d). In addition, the cultivation of sugarcane for ethanol could be expanded (IRENA 2019c).

Heating with biomass includes both high-temperature process heat for industry and low-temperature space heating for homes, apartments and office buildings. The agro-processing industry gets heat using crop residues from farms, while lumber, pulp and paper industries get heat using wood residues from forests. Buildings can be heated through town-scale district heating systems or building-scale furnaces, both of which use feedstocks like wood chips and pellets very efficiently. There is a large potential to expand wood production through improved management of existing forests. Such an approach has doubled the volume of wood in Swedish forests over the last century – and thus increased the potential for energy production and carbon uptake from the forest – without increasing the forests' land area (IRENA 2019a).

Electricity generation from biomass is most often provided through combined heat and power (CHP) systems. These can be designed to utilise a wide range of farm and forest feedstocks and operate at close to 100% efficiency (IRENA 2018b). Power production from biomass is also quite flexible, so it can help to balance output over time on electricity grids with high shares of variable wind and solar power.



An important niche that will need to be efficiently explored is the use of biomass residues generated in biomass-based industries such as pulp and paper, lumber and timber, and food and biofuels. These sectors usually offer large biomass resources in the forms of solid and/or liquid biomass residues that can be used for energy production. To a large extent, the modern part of those industries already taps into those resources, mostly for electricity and heat generation, in stand-alone applications or cogeneration systems. But most often there is significant potential for energy efficiency improvements in the processes so that more electricity and/or heat can be produced from the same resources. Other less readily available biomass resources are often not used at all, given that the industry does not need additional energy. In those situations, specific policies providing incentives for the use of this additional biomass are fundamental.

Transport fuels from biomass would be indispensable for decarbonising the global economy. Transport will become much more electrified, but not everywhere, not in all sectors and not all at once. It follows that there would be a large need for biofuels for several decades to come: REmap envisions a five-fold increase. While EVs will come to dominate light vehicle fleets and will be increasingly powered by renewable electricity, they can only enter markets with well-developed power grids. Moreover, fleets take two decades to turn over. Heavy long-distance freight trucks, marine ships and airplanes are unlikely to be fully electrified due to the higher energy density they require. Hence, a mix of oil-based, carbohydrate-based and lignocellulosic biofuels has to be developed and used.

Bioenergy should be obtained in ways that are environmentally, socially and economically sustainable. There is a very large potential to produce bioenergy cost effectively on existing farmland and grassland, without encroaching upon rainforests, and in surplus to growing food requirements. Pockets of potential that do not involve carbon-releasing land use change – either direct or indirect – include energy crops grown on land made available by raising food crop yields or reducing food waste, as well as set-aside lands or contaminated lands on which food production is prohibited. They also include biogas from agricultural wastes like manure and from municipal solid waste, which can reduce emissions of methane. Greater use could be made of food crop residues and forestry residues, while maintaining sufficient residues to enrich the soil and preserve biodiversity (IRENA 2016a; IEA 2017).

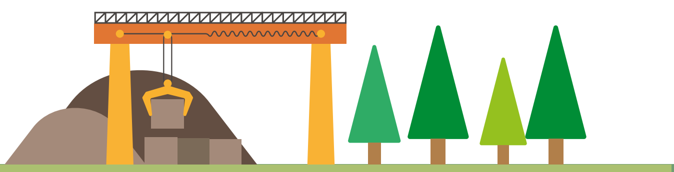
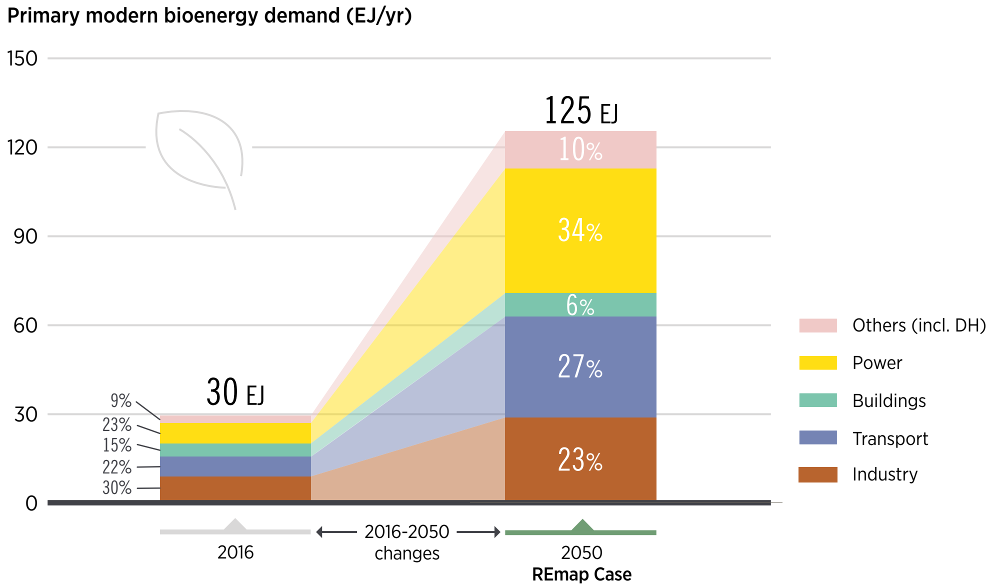


Figure 20. Bioenergy has a decisive role in the energy transition

Primary bioenergy demand in 2016 and REmap Case 2050, (EJ/yr)



Primary modern bioenergy demand would grow from around 30 EJ in 2016 to 125 EJ by 2050. Liquid biofuels consumption would reach 652 billion litres, up from 129 billion in 2016. Biofuels would have important roles in aviation and marine energy supply by 2050, as well as providing thermal energy in industry and fuel for power generation.

In fact, the IRENA analysis shows that the sustainable biomass supply that could be available in 2050 far exceeds the demand for primary biomass entailed in the REmap Case. The REmap Case indicates a total need of around 125 EJ per year of primary biomass to meet all bioenergy demand in 2050. If only agricultural residues and wood residues are taken into account, the potential supply of primary biomass in 2050 would reach 129 EJ to 236 EJ per year. When cultivation of energy crops in land made available from intensification of agriculture and reduction of food waste is considered, an additional potential of 158-313 EJ/year would be added (IRENA 2016a).

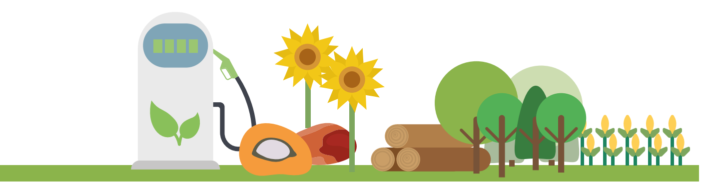
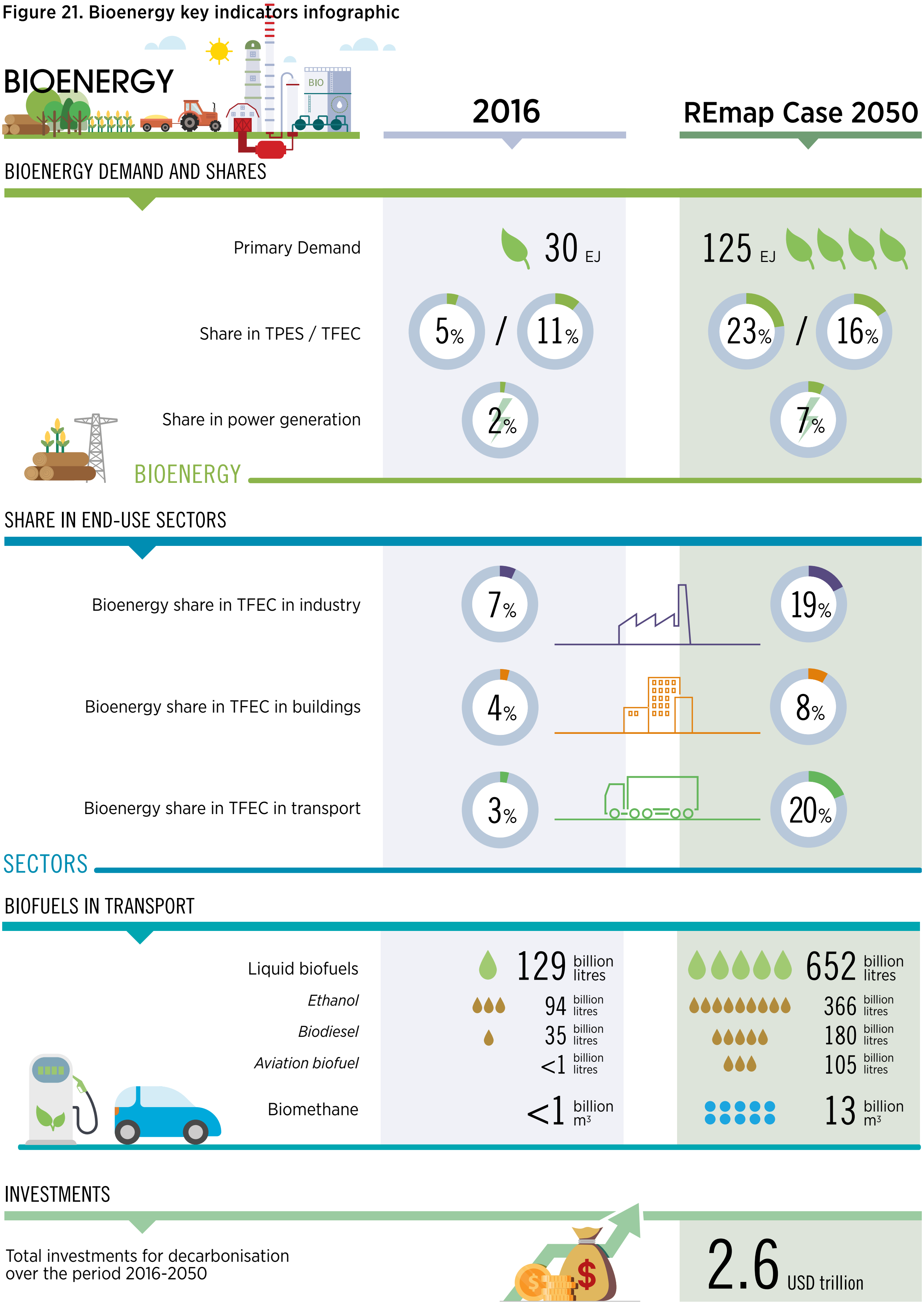


Figure 21. Bioenergy key indicators infographic



Note: The above data are for modern bioenergy sources. Traditional biomass is excluded.

3 INVESTMENTS, COSTS AND REDUCED EXTERNALITIES

3.1 Investments

KEY FINDINGS:

Cumulative investments in the energy system to 2050, including infrastructure and efficiency, will total almost USD 95 trillion in the Reference Case, and would increase to USD 110 trillion in the REmap Case.

A pathway towards meeting the aims of the Paris Agreement will require a shift in investments away from fossil fuels towards renewable energy, electrification technologies and efficiency that would require an additional USD 15 trillion over the period to 2050. The REmap analysis shows that investments of nearly USD 17 trillion should be switched from fossil fuels to low-carbon technologies by 2050.

Implications:

- ***Ensure that investments do not lock in additional fossil-fuel infrastructure.*** Investments in long-term assets, such as in fossil-fuel infrastructure and inefficient buildings stock, are still taking place. These types of investments are not just locking in emissions, they are also adding significant liability and the potential for stranded assets to the balance sheets of energy companies, utilities, investors and property owners.
- ***Develop finance innovations to transform the cash flow from fossil fuel consumption expenditure over time into upfront capital for renewable energy projects.***

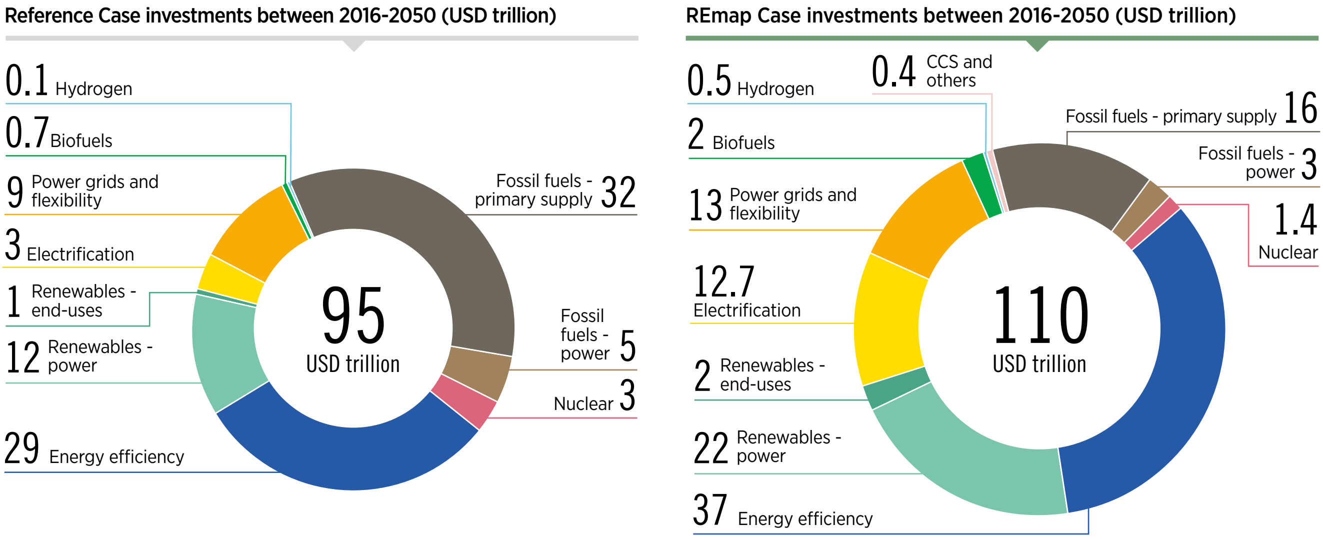
The world is reaching the tipping point where renewable technologies are increasingly becoming the least cost energy supply option. However, investments in renewable energy systems often are different than those for conventional energy systems, with higher upfront investment needs and lower operating costs, and increased need for complementary infrastructure.

Significant increases in investment are required to meet growing global energy demand. In the Reference Case, annual energy-sector investments would need increase by 50% from recent investment volumes in order to meet growing global energy demand. To meet the goals in the Paris Agreement, annual investment would need to double.

To put this in perspective, cumulative investments in the energy system to 2050, including infrastructure and efficiency, would total USD 95 trillion in the Reference Case, and USD 110 trillion in the REmap Case. Around USD 3.2 trillion would need to be invested per year (representing about 2% of average global GDP over the period) to achieve the low-carbon energy system described in the REmap Case. This annual investment is around 17% more than under the current and planned policies of the Reference Case, equivalent to around USD 0.5 trillion more per year. As a reference, the annual investment in the global energy system that took place in 2017 was USD 1.8 trillion (IEA 2018f). The additional investment over the Reference Case is made up of just under half in renewable energy and associated infrastructure and the remaining in energy efficiency and electrification of mobility and heat applications.

Figure 22. Investment will need to shift to energy efficiency, renewables and electrification of heat and transport applications

Cumulative investment – Reference and REmap Cases, 2016-2050 (USD trillion)



Notes: *includes nuclear, carbon capture and storage (CCS); **includes investments in power grids, energy flexibility, electrification of heat and transport applications as well as renewable hydrogen. "Energy efficiency" includes efficiency measures deployed in end-use sectors (industry, buildings and transport) and investments needed for buildings renovations and structural changes (excluding modal shift in transport). Renewables include investments needed for deployment of renewable technologies for power generation as well as direct end-use applications (eg. solar thermal, geothermal) USD throughout the report indicates the value in 2015.

Cumulative investment of USD 110 trillion must be made between 2016-2050 predominantly in low-carbon technologies, averaging around 2% of global GDP per year. The REmap Case requires an increase in investments of USD 15 trillion, but also a significant shift into electrification, renewable energy and energy efficiency technologies which would then cover four-fifths of total cumulative investments over the period 2016-2050.

In the REmap Case, **additional investment is necessary to deploy the solutions and technologies required to reduce the carbon intensity of the global economy by two-thirds by 2050,** which would result in lowering total primary energy supply in that year slightly below 2016 levels, despite an economy that is three times larger than today's.

In absolute terms, investments into the key enabling technologies include:

Power system: Investments in the infrastructure and capacity required to achieve an 86% share of renewables in power generation and 60% of VRE:

- **Renewable power capacity:** The increasing deployment of renewables is taking place in many countries around the world simultaneously. In 2018, renewable energy investments amounted to USD 332 billion (BNEF 2019), slightly lower than the 2017 total of USD 308 billion. **In the REmap Case, investments over the period to 2050 in renewable power capacity would need to increase to more than USD 660 billion per year,** or roughly more than double the investment volumes in renewable power capacity in 2018.
- **Power grids, adequacy and storage:** There are additional components that are considered for investment needs in the REmap Case for the power sector, which enable an adequate and flexible operation of the system. These include transmission and distribution, smart meters, pumped hydro, decentralised and utility-scale stationary battery storage (coupled mainly with decentralised PV systems), and retrofitted and new power generation capacity to ensure generation adequacy. Investment

needs for other flexibility resources, including power-to-heat, power-to-hydrogen, vehicle-to-grid services, demand side management, thermal storage, etc., are not considered in this estimation. **The sum of all these investments for power sector grids, adequacy and flexibility, additional to power generation capacity, total USD 12 trillion in the REmap Case – a third higher than the USD 9 trillion total investments in the Reference Case.** Nearly 83% of the overall investments are needed for extending or enhancing transmission and distribution grids, while the remaining investments are needed for adequacy and flexibility measures (including storage) of the power system.

Renewable technologies in end-use sectors: In the end-use sectors of industry, buildings and transport, investments in renewable heating, fuels and direct uses would need to increase from around USD 20 billion in 2017 to just under USD 73 billion per year over the period to 2050. This is an increase of almost four-fold, and points to the importance of not just scaling up investment in renewable power capacities but also in end-use solutions. More than half of the overall renewables investments in end-use sectors are needed for rapid deployment of solar thermal technologies in industry and buildings, followed by an adequate amount (14%) to be invested for biomass in industrial applications. Adequate investments of nearly USD 2 trillion are needed because of the rising importance of biofuels production to decarbonise the transport sector, especially aviation and shipping.

Energy efficiency: Energy efficiency is the single largest investment need of any of the options considered in the REmap analysis. And if the world is to set itself on a path towards meeting longer-term decarbonisation targets, **investments in energy efficiency would need to be significantly scaled up to USD 1.1 trillion per year, almost five times higher than 2017 investments (USD 242).** The highest share of energy efficiency investments, more than 70%, would be in buildings, mainly in improving building thermal envelopes, deploying efficient appliances and lighting, and replacing buildings early with energy-efficient buildings, among others. Such investments would especially benefit enterprises involved in construction and the production of equipment. Energy efficiency investments often pay back quickly, in the form of reduced energy costs.**Electrification of end-use applications:** Significant electrification in end-use sector demand is key for achieving decarbonisation of the energy sector by 2050.

- **Electrification in transport:** In order to achieve effective decarbonisation by 2050, fossil fuel emissions from the transport sector must be significantly reduced by massively replacing conventional vehicles with electric vehicles. **Yearly investments of around USD 298 billion would need to be made in charging infrastructure for electric vehicles and for the electrification of railways in the REmap Case until 2050.**
- **Electrification of heat:** Rising heat demand in low-temperature regions of the world requires alternative technology options to replace the existing fossil fuel-dependent options. Heat pumps offer a low-carbon technology solution for heat demand in some end-use applications. They are now an attractive option in Europe and are expected to gain momentum in colder regions with high heating demand. **USD 76 billion of annual investments are required to deploy more than 300 million additional units in the REmap Case between 2016 and 2050. More than two-thirds of the heat pumps would be deployed in buildings, with the remaining in industry sectors.**

Hydrogen – the emerging renewable technology option: The REmap Case in this report identifies that by 2050 nearly 19 EJ of global energy demand can be supplied by renewable hydrogen (hydrogen produced from renewable sources). To realise such a potential, **almost USD 500 billion of cumulative investment is needed over the period to 2050.**

Avoided investment in fossil fuels: In order to achieve the climate targets in the Paris Agreement, investments of nearly USD 17 trillion should be switched from fossil fuels to low-carbon technologies over the period to 2050 as highlighted in the REmap Case. This would reduce annual fossil fuel investments to around USD 490 billion – around half of what was invested by the fossil fuel industry in 2017 (IEA 2018f). Reduced upstream oil investments would account for nearly 64% of the total avoided fossil fuel upstream investments, with natural gas accounting for 33% and coal for 4%. In the power sector, investments in fossil fuel power plants would be reduced to half of the investments projected in the Reference Case (USD 4.6 trillion) between 2016 and 2050. Most of those investments would be needed for refurbishing existing thermal power plants, while a small amount would be invested for already commissioned plants which are near completion.

3.2 Investments and costs in a transformed power sector

KEY FINDINGS:

Investment needs for grids, generation adequacy and storage total USD 12 trillion for the period 2016-2050 in the REmap Case, USD 3 trillion higher than in the Reference Case.

Not all investments in a power system are driven by increases in VRE. Some are driven by the increase in electricity demand or high levels of electrification while others are driven by the increased seasonality of demand.

Implications

- **There is a need to shift the focus from integration costs to a cost-effective mix of investments.** In future power systems based largely on solar and wind, the most significant cost component for electricity production will be capital investments instead of operational costs.
- **Electricity markets will need to be redesigned to enable the optimal investments for systems with high levels of VRE.** There is a need to rethink electricity markets and how market design can provide the right signals for cost-effective investments for a least-cost, flexible and reliable power system, as well as how investments compete not only on capex bases but also based on cost of capital.

Energy planners have always had to deal with variability and uncertainty to some extent. **But high levels of VRE pose new challenges for the power sector.** One of the main goals of long-term power system planning is to define the infrastructure and capacity required to enable an effective functioning of the system and the associated investments. Modelling of different possible future scenarios has become a critical planning tool in the power sector to inform long-term investment choices. Modelling and cost estimates are important for ensuring that the share of renewable energy in the power sector will be able to reach 86% by 2050, and 60 % of VRE, in the most cost-efficient ways.

Different methodologies and approaches have been used to estimate the additional costs and investment needs for transformed power systems, defined in the past as "VRE integration" costs. **As VRE becomes the backbone of future power systems, however, this concept becomes outdated.** The reason is that it is based on the impacts of low VRE shares in an inflexible power system designed around fossil fuel generators and a market based on short-run marginal cost pricing, where fuel costs play a large role in the overall costs of electricity supply. Furthermore, grid investments have been treated as "outside of market" and added to consumers' bills at regulated returns.

It is important to note that not all power system investments are driven by the need for more flexibility to accommodate increased VRE generation. Some are driven by the increase in demand due to economic growth and in the future, by high levels of electrification of transport and heating. Others are driven by the increased seasonality of demand (especially for electrification of heat), while others will be driven by consumer preference (for example, the potential preference of consumers for EVs rather than internal combustion engine (ICE) vehicles, due to the possibility of EVs having lower total cost of ownership and fewer restrictions due to air quality policies).

For all these reasons, now the focus needs to shift from integration cost to a cost-effective mix of investments, where the most significant cost component for electricity supply is not fuel anymore.

Instead the greater share of costs will be investments in assets such as solar and wind generators, as well as transmission and distribution grids, storage and flexible demand. This also entails rethinking how market design can provide the right signals to cost-effective investments for a least-cost, flexible and reliable power system. Ideally this should be incentivized through electricity markets (as opposed to outside of the market). In addition, investments should not only compete on capex basis, but also on the basis of the cost of capital, to minimise the cost of a unit of energy for the final consumer.

Given the complexity of developing a global model that addresses medium- and long-term planning for VRE and overall power system development, a high-level simplified approach has been applied to identify potential power systems issues in the REmap Case in 2050. Additional investments required to address these issues have been estimated at the global level, based on a bottom-up analysis of G20 countries. **Based on this, investments in grids, generation adequacy and some flexibility measures (i.e. storage) would total USD 12 trillion for the period 2016-2050 (USD 3 trillion higher than in the Reference Case).**

Nearly 83% of these investments are in transmission and distribution grids. Reinforcement, replacement and expansion of grids are considered to supply projected electricity demand towards 2050. Storage contributes to adequacy and flexibility. It is assumed that storage is deployed widely, including some additional pumped hydro capacity and battery storage as part of decentralized power generation, dedicated utility-scale batteries and also assuming that some of the EV battery capacity would support the grid through V2G services. A description of the approach applied for the calculation of investments needed for adequacy and flexibility is provided in the box below.

Box 3. SIMPLIFIED APPROACH TO ASSESS GENERATION ADEQUACY AND FLEXIBILITY INVESTMENT NEEDS

The REmap analysis substitutes fossil and nuclear energy in the Reference Case with renewable energy, resulting in a power capacity mix for the REmap Case. Given that there is no power system analysis carried out in this new scenario, generation adequacy and flexibility issues are assessed based on the following approach:

Generation adequacy assessment: The assessment serves as a sensitivity analysis to estimate any need for additional generation capacity to ensure adequacy. It consists on estimating whether there is enough firm capacity to cover load, as well as to provide electricity throughout a day or a whole week under extremely low renewable energy resource availability. Low renewable energy availability could be caused by several factors, including dry years (i.e. years with low water availability), low biomass feedstock, no wind or no sunny hours. Firm capacity is provided to the system through power generation capacity, stationary battery storage and battery storage from EVs, along with load shifting through demand side management. If there is a lack of firm capacity in the REmap Case, additional power generation capacity and the associated investments are estimated, considering options that include retrofitting power capacity that would have been otherwise retired and new natural gas power generation if needed.

Sources of flexibility: Considering the important roles that electrification, sector coupling, storage and demand side management will play in the coming years, power systems will benefit from several flexibility resources. There are several technologies that contribute to this flexibility in a power system. For the simplified approach in the REmap analysis, investments related to pumped storage, and stationary batteries for decentralized power generation and utility-scale batteries were estimated. Other investments that are required for other flexibility measures like demand side management, power-to-X, V2G, etc., are not captured in this analysis.

Box 4. THE COST OF VRE INTEGRATION THROUGH THE LENS OF THE ENERGY TRANSITION

Estimating the costs and benefits of integrating variable renewable energy (VRE) sources into power systems has been a topic of interest for more than ten years now since the shares of wind and solar started increasing in the global energy mix. The relative importance and magnitude of different types of costs and benefits related to VRE integration depend on factors like the physical structure of the power system, the regulatory framework and the stage of VRE deployment. The main economic benefit from VRE deployment is related to fuel savings from replacing fossil fuel generation in the energy mix. There are also social benefits from avoided CO_2 production and other pollutants like PM, NOx and SOx, however, externalities from pollutants are not always considered in such studies.

Costs of VRE are mainly related to the inherent characteristics of VRE sources, namely variability, uncertainty and location dependency (IRENA 2018h). Integrating solar and wind power into power systems can potentially affect their ability to balance real-time supply and demand and efficiently recover from unexpected events. A power system that can effectively perform the above functions is said to possess sufficient flexibility (IRENA 2018a).

At very low shares of VRE, variability and uncertainty can be managed through making low-cost changes in operational practices like creating intra-day markets with higher temporal resolution and gate closure closer to actual dispatch, or simply improving dispatch and forecast practices. During the early stages of VRE deployment, the main economic impacts are related to increased needs for flexible generation and operational reserves to manage variability and uncertainty. Such costs are mainly operating expenses (OPEX) and are related to suboptimal unit commitment and dispatch of the non-VRE parts of the system. They are also frequently referred to as balancing costs (Ueckerdt et al. 2013). In many places around the world, enhancing the transmission network has been identified a key measure to unlock existing flexibility in grids. The so-called “grid costs” are the main type of capex costs that traditionally have been needed for low VRE shares. The definition of grid costs varies in literature. In some studies, grid costs are defined as the cost to connect VRE with the main transmission network. In other studies, it is both the cost of connection and transmission enhancement investments.

Previous VRE integration studies around the world, mostly initiated by utilities, system operators and large national institutions during the period 2000-2013, have been mainly focused on assessing technical and economic impacts of low to medium VRE shares (DeMeo *et al.* 2005; GE Energy Management Energy Consulting 2010, 2010; Gross *et al.* 2006; Holttinen *et al.* 2009; Lew et al. 2013; NREL 2011). But now, VRE deployment is rapidly reaching higher shares. Shares of VRE higher than 60% have been achieved today in some small island grids (e.g. King Island and Flinders island) (Kroposki 2017). Denmark and Ireland are front runners of wind integration with wind shares of 44% and 27%, respectively, and maximum instantaneous penetration beyond 150% and 60% of demand, respectively (EirGrid and SONI 2018; RTE 2018). South Australia has achieved a VRE share of 48%, while Germany, Lithuania and Spain have achieved more than 20%. This practical experience shows that achieving very high shares of VRE is currently technically possible. As a result, the limit to renewable energy penetration is mainly economic, driven by factors like system flexibility.

In systems without VRE, flexibility has traditionally been associated with the supply side of the power system. Profile costs, another element of grid integration costs found in the literature, is defined as the investment costs needed for dispatchable capacity due to the low firm capacity of VRE. The use of profile costs is based on the notion that focusing on the supply side of a power system is the only way

Box 4. THE COST OF VRE INTEGRATION THROUGH THE LENS OF THE ENERGY TRANSITION (continued)

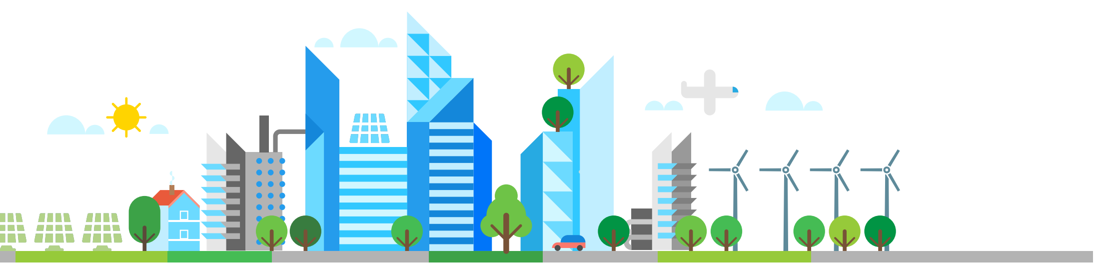
to ensure generation adequacy. However, this approach fails to account for the role of flexible demand in ensuring adequacy and reliable operations.

To effectively manage large-scale VRE deployment, additional sources of flexibility need to be deployed by planning ahead of time. Flexibility has to be harnessed in all sectors of the energy system, from power generation to stronger transmission and distribution systems, storage (both electrical, thermal and through green gas) and more flexible demand (demand-side management and sector coupling) (IRENA 2018f).

As the VRE share increases, there will be a point where significant investments on flexibility enablers will be needed to manage variability and uncertainty in power systems. In addition, at very high shares of VRE, thermal generation will be minor compared to VRE and storage capacity. Thus, assessing balancing costs will be irrelevant for the big picture. At high VRE shares, the great majority of costs will be investments on solar and wind generators, transmission and distribution grids, digital control equipment, storage (both stationary, EVs and seasonal (*e.g.* through hydrogen) and flexible demand (including demand side management, heat pumps and electric boilers).

The total CAPEX costs for transforming a power system varies case by case. For example, the total need for investments on enabling technologies depends on factors like existing flexibility and demand growth (due to both economic growth and electrification). This is because enhancing flexibility is less costly in a greenfield investment, as opposed to investing in suboptimal solutions in systems with overcapacity. Moreover, the temporal change of demand shape depends also on seasonality of demand (especially for electrification of heat) as well as consumer preference (e.g. EVs being a superior product to internal combustion engine (ICE) vehicles).

Finally, investments in VRE will only take place if investors can make reasonable profits. This requires systemic innovation on policies, market design and regulatory frameworks. As an example, investment decisions depend on the weighted average cost of capital (WACC) in addition to capital costs, so efforts must be made to lower the WACC. For example, the BNDES National Climate Change Fund in Brazil offered low-cost, long-term loans with interest rates as low as 2% for up to 70% of the total capital requirements of RE projects, effectively outperforming private banks (IRENA 2016c).



3.3 Stranded assets

KEY MESSAGES:

Due to the slow progress to date in reducing emissions from the energy sector, USD 11.8 trillion in current assets would be stranded by 2050 if the world did reduce emissions enough to meet climate targets, even if progress started today.

Delaying decarbonisation of the energy sector to 2030 or beyond would increase the stranded assets to USD 19.5 trillion.

Implications

- ***Countries need to properly assess the risks of investing in high-emissions technologies and optimise their investment decisions required to meet a well below 2°C target.***
- ***Policy makers need to tackle such potential issues as unemployment or fewer well-paid jobs, lower tax revenues, lower dividend payments, higher rates of loan default and lower rates of corporate solvency that will result from stranded assets.***
- ***Financial institutions must undertake an investment risk analysis and asset evaluation to ensure that the expansion of the global energy system leads to a climate-compliant scenario.***

To reduce the risk of stranded assets, action has to be taken quickly and investments must be channelled into climate-friendly energy technologies. If action begins immediately to reduce emissions in line with a pathway compatible with the Paris Agreement, the amount of stranded assets would be USD 11.8 trillion by 2050, as identified in the REmap Case. These stranded assets are the result of current slow progress in reducing emissions in the energy sector.

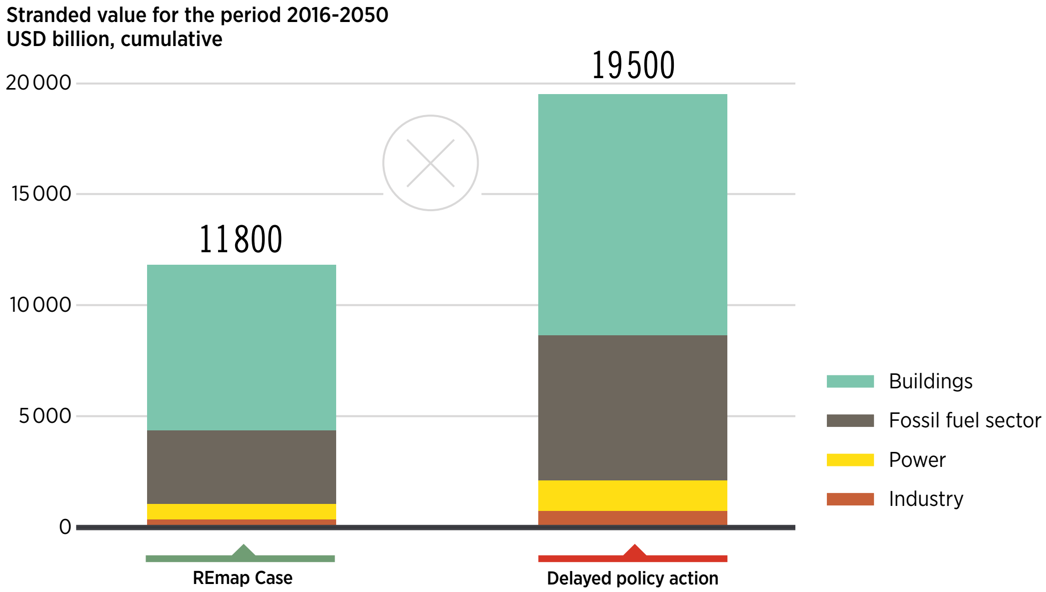
Stranded assets in this analysis result from the need to prematurely retire and replace carbon-intensive assets that are incompatible with well below 2°C climate targets. In this analysis, remaining within the carbon budget will require: 1) the replacement of fossil fuel energy with renewable energy technologies, and 2) early retrofits to improve energy efficiency. There are, therefore, implications for the entire fossil fuel industry, from upstream production through power generation and energy use in industry and buildings.

The amount is substantial. **It equals about one-third of additional investment needs or around 3% of today's global capital stock.** However, delaying decarbonisation of the energy sector (for example, starting only in 2030) increases the risk of carbon lock-in and would make the energy transition more expensive. It would double the assets stranded between today and 2050 to a total of USD 19.5 trillion – or USD 7.7 trillion more than in the case of immediate action. Delaying the shift away from fossil fuels to low-carbon technologies is a risky and expensive strategy, therefore, especially for buildings and the fossil fuel supply sector.

In addition, delaying action could make it necessary to adopt costly technologies for removing carbon from the atmosphere (negative emission technologies, such as bioenergy with carbon capture and sequestration) in order to stay within the emissions envelope.

Figure 23. Stranded assets increase significantly if action to decarbonise the energy sector is delayed

Total stranded assets for the REmap Case and the Delayed Policy Action Case (left) and by sector for the REmap Case and Delayed Policy Action Case (right), cumulative for the period 2016-2050 (USD billion)



If Paris Agreement aims are met, the resulting stranded assets would amount to almost USD 12 trillion by 2050. This equals about one-third of additional investment needs or around 3% of today's global capital stock. Delaying action, however, would increase those losses to as much as USD 20 trillion.

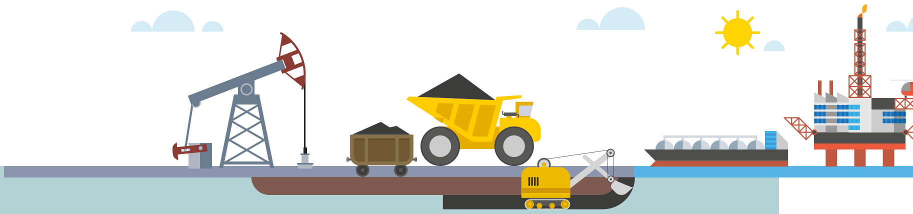
If countries and financial institutions adopt a free rider strategy, or if they avoid proper investment risk analysis and asset evaluation, global temperatures are likely to rise more than 2°C. That will be much costlier (in all aspects) for the global economy and societies than investing now in a well below 2°C scenario. **A massive shift of investment flows, towards renewables and energy efficiency, is needed to minimise stranded assets.**

Asset stranding directly (and indirectly) affects the owners of assets, operators of assets and the localities, regions and countries where assets are located. The impacts can include unemployment or fewer well-paid jobs, lower tax revenues, lower dividend payments, higher rates of loan default and lower rates of corporate solvency. All these impacts will be different depending on the assets being stranded, the sector that they are in and where they are being stranded.

Stranded assets can also impact the financial system. They can reduce the solvency of individual financial institutions exposed directly or indirectly to stranded assets. Through the rapid repricing of assets, stranding could potentially cause a climate-change "Minsky" moment, where a sudden collapse of asset prices leads to a financial crisis. This is more likely if policy action on climate change is delayed. The costs of these outcomes would be absorbed by financial institutions, as well as by society through impaired lending and financial service provision, and potentially significant publicly-funded bailouts.

The challenge for policy makers navigating the transition is to optimise the total investments required to meet a well below 2°C carbon aim and to minimise the amount of stranded assets. Countries have the opportunity to lower risks and reduce uncertainty by taking timely actions to decarbonise their energy sectors and to handle the resulting stranded assets and the consequences and implications. Properly assessing the risks of investing in high-emissions technologies is one of the key steps to ensure this.

3.3.1 Fossil fuels



KEY FINDINGS:

By 2050, fossil fuels use would fall by two-thirds from today's levels, given accelerated global uptake of renewables.

Stranded assets in the fossil-fuel upstream sector would amount to USD 3.3 trillion by 2050 with the envisaged shift to renewables. But this would almost double to USD 6.5 trillion if action is delayed.

Implications

- ***Curtail investments upstream.*** The most direct way to influence today's investments would be for governments to re-evaluate their own upstream investments. Reducing them today will prove to be an important measure in reducing the total value of stranded assets in the future.

- ***Encourage firms to increase disclosure of their risk exposure to climate change and the decline in fossil fuel markets.*** Better information improves the understanding and analysis of risks, and over time, promotes a smooth rather than an abrupt transition towards a lower-carbon economy. Oil and gas sector companies could more speedily shift to investing in clean energy technologies as part of their businesses.

- ***Set higher standards for new buildings and encourage energy efficiency retrofits of existing ones.*** Commercial and residential buildings have the highest risk of stranded assets. The implementation of standards that promote a prompt adoption of clean technologies and energy efficiency can serve to reduce this risk.

- ***By 2050 in the REmap Case, fossil fuel use would fall by two-thirds.*** Fossil fuel consumption would continuously decline from 2020 onwards. By 2030, demand for fossil fuels would decline by 21%, and by 2050 by 66%. Oil and coal would decline moderately until 2020 and then accelerate their declines towards 2050. Natural gas would peak around 2025 and would be the largest source of fossil fuel by 2050. However, production would decline around 40% from the present level and become half of its peak level.

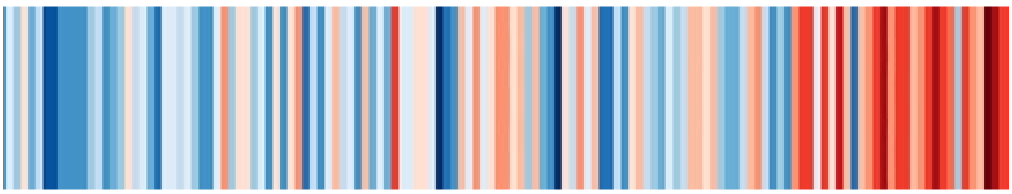
Fossil fuels will still have roles to play, providing one-third of the energy supply in 2050. However, global production of oil will decline to just above 20 million barrels per day, roughly 80% lower than today. Oil will largely be used in industry for petrochemicals, and in aviation and shipping. Coal production will decline further, to just above 700 million tonnes per year, from over 5 000 million, and be largely used only in industry, mostly for steel production. Natural gas will see production increase, but then decline. It will become the largest source of fossil fuels by 2050, with around half consumed in industry for process heating and CHP, and the remainder being used in power generation, in the buildings sector for heating and in petrochemicals.

Table 2. Fossil fuel demand

Fossil fuels

	2010	2017/2018	REmap Case 2030	REmap Case 2040	REmap Case 2050
Oil demand	87 mln barrels/day	95 mln barrels/day	60 mln barrels/day	41 mln barrels/day	22 mln barrels/day
Natural gas demand	3 307 bcm	3 752 bcm	4 000 bcm	3 400 bcm	2 250 bcm
Coal demand	4 963 Mtce	5 357 Mtce	3 190 Mtce	2 000 Mtce	713 Mtce
Reductions relative to today	NA	NA	-20%	-41%	-64%

Historical data (2010,2017/18) based on IEA energy statistics (IEA 2018c)

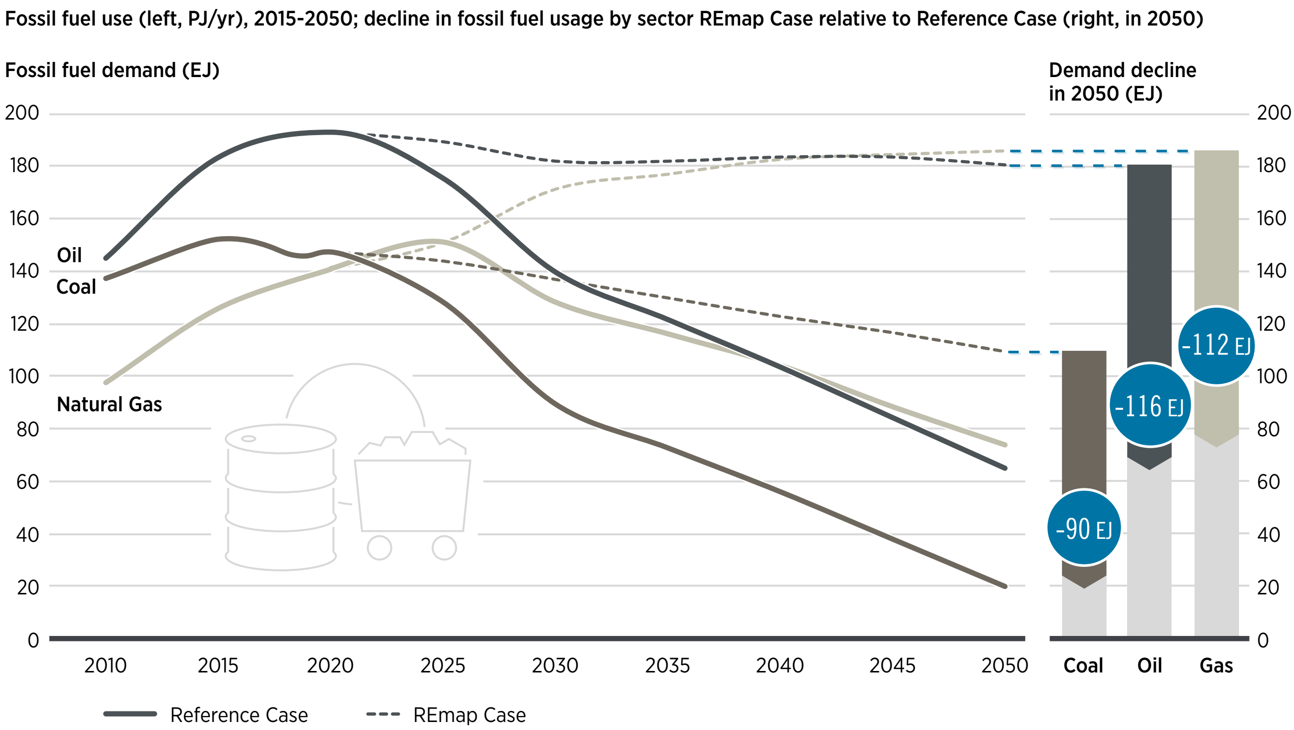


Annual temperatures in Germany from 1881-2017
The colour scale goes from 6.6°C (dark blue) to 10.3°C (dark red)

Planning must begin now to minimise the impact of significantly lower fossil fuel demand on oil and gas companies. The total value of assets stranded in the fossil fuel upstream sector would be USD 3.3 trillion by 2050 in the REmap Case. Delaying action would cause the value of stranded assets to rise to 6.5 trillion by 2050 – almost double. In the REmap Case, fossil fuel subsidies would be reduced from USD 0.45 trillion in 2015 to under USD 0.1 trillion in 2050. Dissemination of action plans for the decommissioning of fossil fuel plants and further enhancement of financial market and pension fund regulation to deal with fossil fuel investment risks are needed.

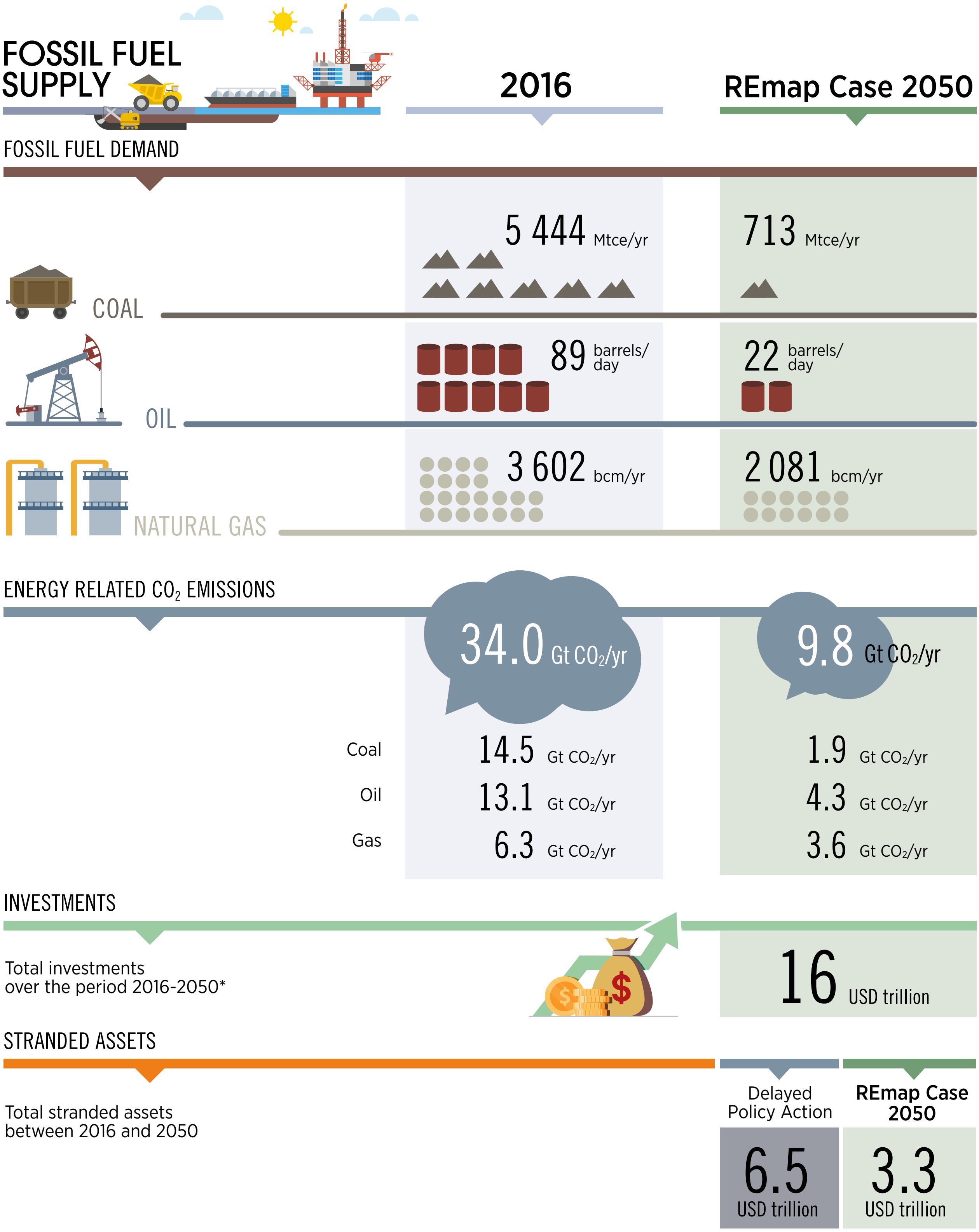
Figure 24. The declining importance of fossil fuels

Fossil fuel use (left, PJ/yr), 2015-2050; decline in fossil fuel usage by sector in the REmap Case relative to the Reference Case (right, in 2050)



With accelerated uptake of renewables, both oil and coal demand decline significantly and continuously, with natural gas demand peaking around 2025. Natural gas would be the largest source of fossil fuel in 2050.

Figure 25. Fossil fuel key indicators infographic



Note: *this includes just the upstream investments, whereas fossil power is included in the power sector infographics

Box 5. CARBON CAPTURE USE AND STORAGE, AND CARBON CAPTURE AND STORAGE

The technical potential of carbon capture and storage (CCS) is significant in parts of the world but progress has been slow. There are now 43 large-scale facilities – 18 in commercial operation, five under construction and 20 in various stages of development. According to the Global CCS Institute's database (Global CCS Institute 2018), those large-scale CCS facilities are capturing almost 40 Mt per year of CO_2. A further 28 pilot and demonstration-scale facilities are in operation or under construction. Collectively, these capture more than 3 Mt per year of CO_2.

Development of CCS has been hampered by the high mitigation cost, the lumpiness of investments, technological setbacks, NIMBY (not in my backyard) concerns, and uncertainty regarding long-term policy commitments. At this stage, CCS appears unlikely to play a major role. However, for certain processes, such as cement clinker making and waste incineration plants, no other major mitigation option is on the table. Therefore, CCS warrants further discussion.

Carbon capture use and storage (CCUS) is a concept to commodify CO_2 that has been captured by using it as a feedstock in manufacturing, so it becomes "stored" in manufactured goods. It is understood as an attempt to make carbon capture and storage (CCS) profitable and perhaps uncouple it from Enhanced Oil Recovery. Some CCUS scenarios are still theoretical, while other technologies are being commercialised.

The primary critique of CCUS is that emissions are not effectively removed or sequestered but are embedded in products that will eventually re-release CO_2 into the atmosphere (e.g. they will be incinerated as waste or decompose). If fossil carbon is recycled once, emissions are halved, which is not in line with total decarbonisation.

Another issue is the obvious mismatch of volumes. Around 35 Gt of CO_2 energy and process emissions are emitted per year. In comparison, only 500 Mt of synthetic organic products are produced (Gielen and Saygin 2018), which is the equivalent of about 1 Gt of embedded CO_2. If the use of bitumen for asphalt is added, which amounts to nearly 100 Mtoe, it adds the equivalent of approximately 0.25 Gt of CO_2. More carbon is used for wood products and new hydrocarbon construction materials may offer potential. Given today's markets, the total storage potential is only 3% of total emissions. Therefore, CCUS constitutes a niche application in the REmap scenario limited to a few applications in industry. Nonetheless, the there is a need to scale up to over one gigatonne to address CO_2 in a few industry segments, specifically cement, iron and steel and chemicals.

Use of bioenergy in combination with CCS offers the prospect of negative emissions. The Drax Power Station in the United Kingdom (UK) has started carbon capture from biomass burning, but on a small scale. The hope is that the Drax pilot project, which is capturing 1 tonne of carbon dioxide a day, will pave the way for a large-scale roll out of the technology, which could eventually pull 10 Mt a year of CO_2 out of the power plant's smokestack. However, the pilot under way at the North Yorkshire facility is not storing any carbon dioxide. Instead, it is re-releasing the captured CO_2 into the atmosphere, because the company has not yet worked out what to do with it (FT 2019c).

Biomass CCS has not been included in the REmap Case by 2050, but it offers a prospect of zero emissions. For example, it features prominently in the EU's long term decarbonization scenarios. In the EU alone, the potential of existing biomass plant is in the order of 100 Mt per year (Fridahl, M. 2018).

3.3.2 Nuclear energy

In 2018, about 450 nuclear power reactors were operating in 30 countries, with a combined capacity of about 400 GW (WNA 2019). In 2017, these provided 2 506 TWh, over 10% of the world's electricity. This is a significant decline from a peak of about 17% some years ago. About 50 power reactors are currently being constructed in 15 countries, notably China, India, Russian Federation and the United Arab Emirates (WNA 2019). China and Russia are the leading providers of new nuclear technology worldwide, the group of suppliers is shrinking as economics are unfavourable and regulatory requirements become more stringent.

The UK experience exemplifies this challenge. In 2018, Hitachi shelved its new nuclear power station project at Wylfa in Wales, UK. The company formally resolved to halt the USD 26 billion project in January 2019 (The Guardian 2019). It will write off USD 2.8 billion of work in progress. Toshiba quit a similar project at Moorside in Cumbria, UK last year (The Guardian 2018). EDF's plant at Hinkley Point in Somerset, the only new UK reactor already under construction, will receive around USD 130 per megawatt-hour for its electricity (plus inflation correction). The price on the table at Wylfa was about USD 100 per MWh, with a price below USD 80 per MWh for later reactors on the site (FT 2019a). These costs are higher than for wind or solar electricity generation.

Ten years late and two-and-a-half times over budget, Finland's TVO's Olkiluoto-3 EPR is set to start production in 2019, with full operation scheduled in 2020 (WNN 2018). Eight years late and, at USD 12 billion, three times over budget, EDF's Flamanville 3 EPR in Normandy in northern France is due to deliver its first power in the summer of 2020 (Reuters 2018).

In Japan, public opposition continues to be strong. As of early 2019, only nine reactors had restarted after the country's entire nuclear fleet was shut down in the aftermath of the Great East Japan Earthquake on March 2011. Before the Fukushima Daiichi Nuclear Power Station accident caused by that earthquake, 54 commercial nuclear reactors were in operation with a total generation capacity of 49 GW, and nuclear generated about 30% of all of Japan's electricity (Power magazine 2019b).

Older nuclear reactors in Europe and the United States are struggling because operating and maintenance costs alone often exceed the production costs of new renewable generation capacity (Power magazine 2019a).

There is a new emphasis on small-scale reactors that could potentially fit better with the trend towards a more decentralized power supply. New efforts are also focused on greater flexibility of nuclear reactors as inflexible baseload is problematic in power systems with high shares of variable renewables.

Nuclear power is CO_2 neutral, which is beneficial in a severely carbon constrained world. However, cost have tended to increase over time while cost of renewables have fallen substantially. Waste and risk aspects add to the complexity of it as a supply option. For countries that choose to support nuclear energy, this option can play an important role in mitigating CO_2. The REmap Case assumes roughly a stabilization of nuclear power generation at today's level, which means that replacement investments take place, but no nuclear renaissance is assumed. The REmap Case does not consider nuclear fusion as the lead time for commercial applications will be several decades, with first commercial reactors are at best expected mid-century.

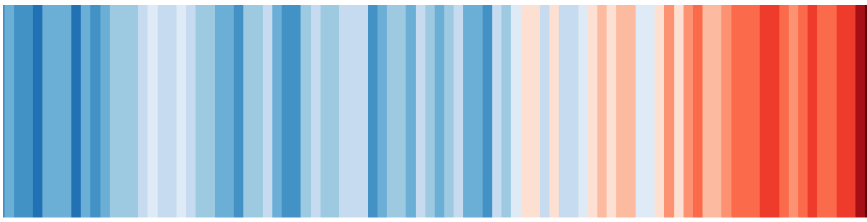
3.4 Costs, externalities and subsidies

KEY FINDINGS:

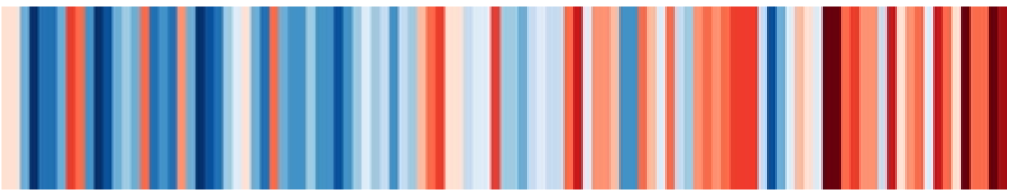
Cumulative savings to 2050 from reduced subsidies and externalities, such as a decline in air pollution, lower health costs and less environmental damage, outweigh the increase in energy system costs by a factor of three to seven.

Implications:

- ***Internalise large external costs.*** Internalisation of costs, such as pollution, clearly provides a better approach than current practices for setting future policy priorities. Governments could incorporate these costs into typical market structures through financial incentives such as carbon pricing and possibly also by pricing local pollutants.
- ***Create more effective and improved regulations to limit air pollution.*** Measures such as fuel efficiency standards and monitoring indicators applied in all sectors can support the uptake of cleaner and more efficient technologies.
- ***Coordinate policy and regulation to better capture the benefits of renewable energy and energy efficiency with economic mechanisms.***

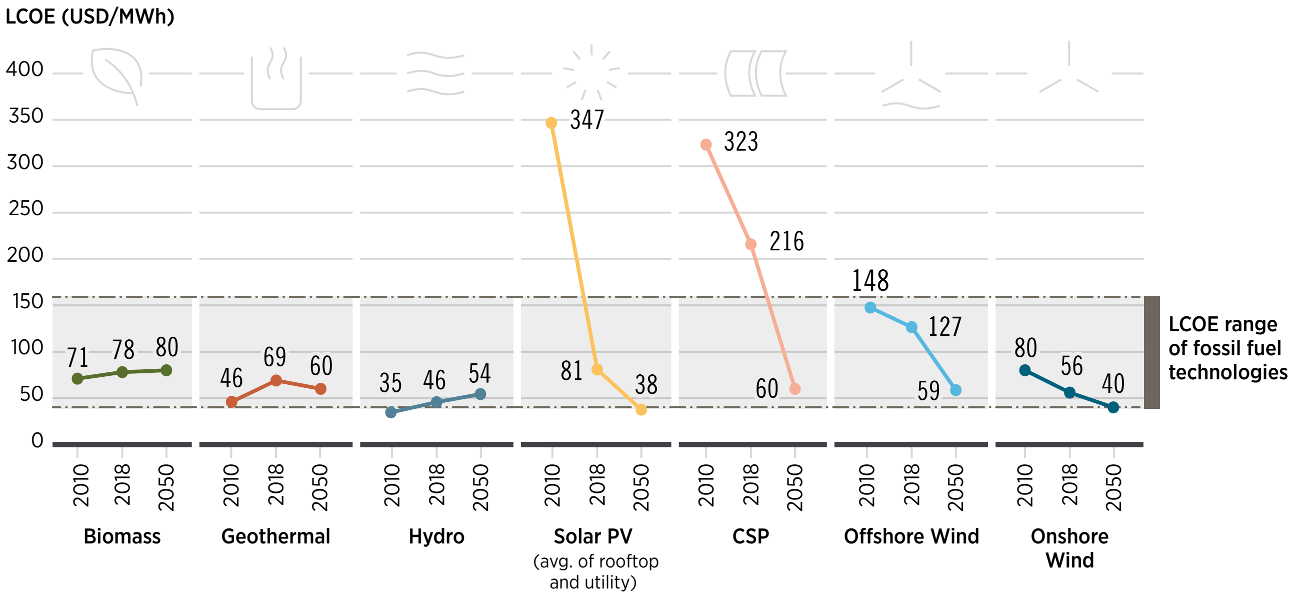


Renewable power technologies are increasing the least-cost electricity supply options available. The growth of the renewable energy market is expected to accelerate as costs decline, technologies improve, and innovation brings additional applications. A huge market is emerging. Almost USD 90 trillion of renewable energy, electrification technologies and energy efficiency investment are needed until 2050. In 2030, the renewable energy market would reach USD 730 billion per year, and in 2050 USD 680 billion.



Annual temperatures for New Zealand (1909-2017)
The colour scale goes from 11.3°C (dark blue) to 13.4°C (dark red)

Figure 26. The renewable energy technologies are reaching the tipping point and becoming increasingly competitive



With accelerated uptake of renewables, both oil and coal demand decline significantly and continuously, with natural gas demand peaking around 2025. Natural gas would be the largest source of fossil fuel in 2050.

Combined with reduced fuel expenditures, the investments in renewable energy and infrastructure over the period to 2050 make it possible to calculate how the cost of the entire energy system would change. The result of this transformation would be a slight annual increase in energy system costs, amounting to USD 1.0 trillion in 2050, or about 0.4% of global GDP in that year. However, only 10% of the incremental cost is directly related to renewable energy or energy efficiency measures. The largest component, around half, is related to complementary infrastructure investments in power grids and energy flexibility. Meanwhile, one-quarter is related to the retrofitting or early replacement of buildings to make them more energy efficient, and 15% is the additional cost of CCS deployed in certain industry sub-segments.

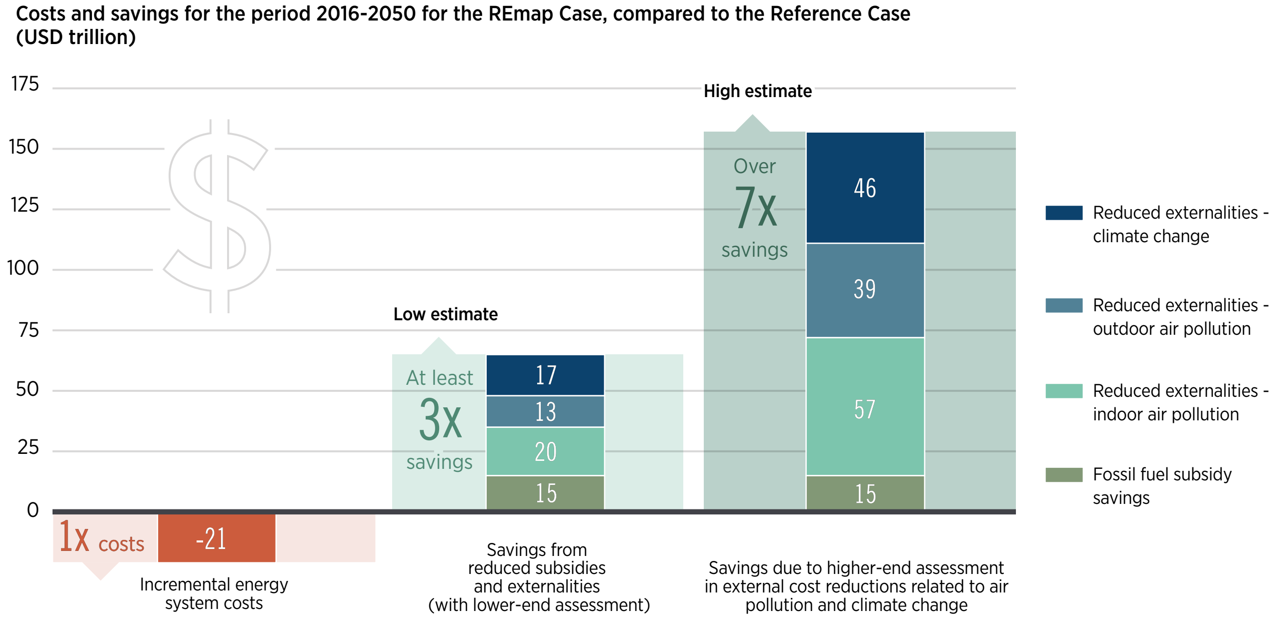
Overall, the cost savings from reduced externalities significantly outweigh the incremental investment needs in the energy system. Shifting the energy mix from the Reference Case to the REmap Case saves fossil and nuclear fuel for energy production that adds up to an average of USD 2.8 trillion annually, or a total of USD 96 trillion over the period to 2050. Further savings come from reduced air pollution, lower healthcare costs and less damage caused by the many impacts of climate change. Gains in human health (a fundamental driver of energy policy in many countries) and lower CO_2 emissions from fossil fuels would generate savings on average of USD 5.7 trillion annually by 2050. If the higher end estimate is used, cost savings would be as much as USD 7.7 trillion per year. Moreover, these savings do not take into account such additional benefits as lower water consumption, greater job creation and higher GDP. The analysis also suggests that there would be a general improvement in welfare.

Therefore, the energy transition is cheaper than not making the transition, in addition to being necessary to meet global climate and sustainability goals. In total to 2050, benefits from reduced (net) subsidies and reduced health and environmental externalities exceed the investment costs by three to seven times. In other words, for every additional dollar spent on the energy transition between now and 2050, there are USD 3-7 worth of payoffs derived from fuel savings, avoided investments and reduced externalities during the period 2016-2050. Cumulative net savings over the period would be between USD 45 trillion and USD 140 trillion – up to almost two times an entire year of current global GDP.

These benefits can be reaped with low additional investments compared to the Reference Case up to 2030. After 2030, no additional investments are needed (compared to the Reference Case). On the contrary, required investments actually drop in the REmap Case because of the declining costs of renewable technologies.

Figure 27. Investing in the energy transition is beneficial for society

Breakdown of system costs, subsidy savings and reduced externalities savings for the period 2016-2050 (USD trillion)



Note: Subsidy savings represent the net of additional savings for renewables and efficiency and avoided subsidies in fossil fuels. Low and high estimates of savings are applicable only to reduced externalities with respect to pollution and climate change, while the net savings from fossil fuel subsidies remains constant (USD 15 trillion). Incremental investments and costs/savings for the period 2016-2050

For every dollar spent for the energy transition, the payoff amounts to at least three dollars and, depending on how externalities are valued, up to seven dollars. The total net payoffs from accelerated uptake of renewables – combined with energy efficiency and electrification – would be between USD 45 trillion and USD 140 trillion over the period to 2050.

As renewables rise, net energy subsidies fall, as do health costs from air pollution and climate impacts. Half of the USD 21 trillion in additional expenditures, including investment and operational costs, could be covered by the savings on avoided subsidies.

Box 6. SOLAR AND WIND POWER GENERATION COSTS WILL CONTINUE TO FALL TO 2030 AND BEYOND

Between 2010 and 2018, the cost of electricity from solar photovoltaics fell by 75%, concentrating solar power (CSP) by 39%, onshore wind by 33% and offshore wind by 20% (IRENA 2019e). In 2018, the global weighted average cost of electricity of projects commissioned – under a conservative weighted average cost of capital of 7.5% for the OECD and China, and 10% elsewhere – for solar PV was USD 88/MWh. For onshore wind, it was USD 55/MWh, for offshore wind USD 132/MWh and for CSP USD 202/MWh. While these are global average costs, many individual projects result in costs that are below these values.

Available data from auctions, tenders and power purchase agreement (PPA) contracts around the world suggest that costs will continue to fall in the next few years and beyond. (Lead times for completion of the winners of these competitive procurement processes for solar PV and onshore wind, the bulk of the data, are in the range of one to three years depending on the nature and conditions relating to the contracts.)

In 2019, the global weighted average cost of electricity from solar PV is likely to fall to around USD 55/MWh and that of onshore wind to around USD 51/MWh (and USD 49/MWh in 2020). The results of the recent competitive procurement processes should see offshore wind and CSP at between USD 55-97/MWh and USD 62-93/MWh, respectively, in the early 2020s. Continued technology improvements, economies of scale, manufacturing efficiencies and more competitive supply chains will combine with experienced project developers to continue to drive down costs out to 2030 and beyond.

IRENA's forthcoming analysis of the cost reduction potential for solar and wind to 2030 in the G20 will provide detailed estimates of the cost reduction opportunities in each G20 country. The analysis draws on a detailed bottom-up analysis of technology trends and a top-down analysis of global market drivers to arrive at these differentiated results.

For instance, continued improvements in efficiency for solar PV will reduce costs per watt both in the module and balance of system (BoS) costs. In the period to 2025, a key driver of these efficiency improvements will be the shift to increasing shares of PERC (Passivated Emitter Rear Contact) cell architectures, in which a layer of material on the back of solar cells boosts their efficiency. Over the longer term, newer architectures with even higher efficiency levels will take up the baton and drive further improvements. In terms of components, the ingot/wafer process cost reductions will be driven by expected polysilicon cost reductions, lower kerf losses and the increased ability of manufacturers to produce high quality polysilicon at lower costs as manufacturing optimisation drives down energy usage. At the cell level, it can be expected that diamond wire usage will continue to reduce waste and that silver paste costs will continue to decline. At the module assembly level, the cost reductions for PV glass and for frame and encapsulant components are likely to continue until 2030. Although BoS cost differentials have declined as competitive pressures have increased, continued convergence towards best practice levels will be an important cost driver until at least 2025. The drivers for this are more mature markets, the modular, low risk development profile of solar PV (even more so than other renewable technologies) and even greater competition among project developers. Reductions in soft costs will also contribute, as permitting gets simpler and BoS hardware components continue to optimise design and installation practices as deployment continues.

Box 7. ENERGY SUBSIDIES

Policy makers are interested in minimising the costs of the energy transition (and maximising the benefits). However, there are many metrics that can be used to assess the costs of the energy transition. Different metrics yield different insights depending on the questions being posed and the interest of the audience. Important metrics that can help inform decision makers include the changes in GDP and net societal wealth, taking into account the environmental costs and benefits. These metrics can provide a very high-level view of the overall costs and benefits of the transition. In practical terms though, policy makers need to understand what is driving those high-level changes and how sensitive they are to different inputs or assumptions on technological progress, performance improvements and cost reductions. Policy makers will therefore seek other cost metrics that allow them to understand these nuances.

The energy sector has, for virtually all of the modern era of energy use, operated (indeed has often actively sought) a range of subsidies that have distorted market functioning to a greater or lesser extent. However, subsidies can be justified where they are correcting for market failures. They may not be the most efficient way to economically address market failures, but when real world political constraints mean that first-best policies are unavailable, subsidies can still lead to improvements in economic efficiency.

IRENA has examined the evolution of total energy sector subsidies in the energy transition, and presents the evolution of subsidies to 2050 in Figure 19. Total energy sector subsidies were estimated to be around USD 606 billion in 2015. These estimates should be considered a lower bound, as it is difficult to evaluate and calculate a value for a wide range of energy sector subsidy policies. There are therefore significant knowledge gaps remaining in our understanding of total energy sector subsidies.

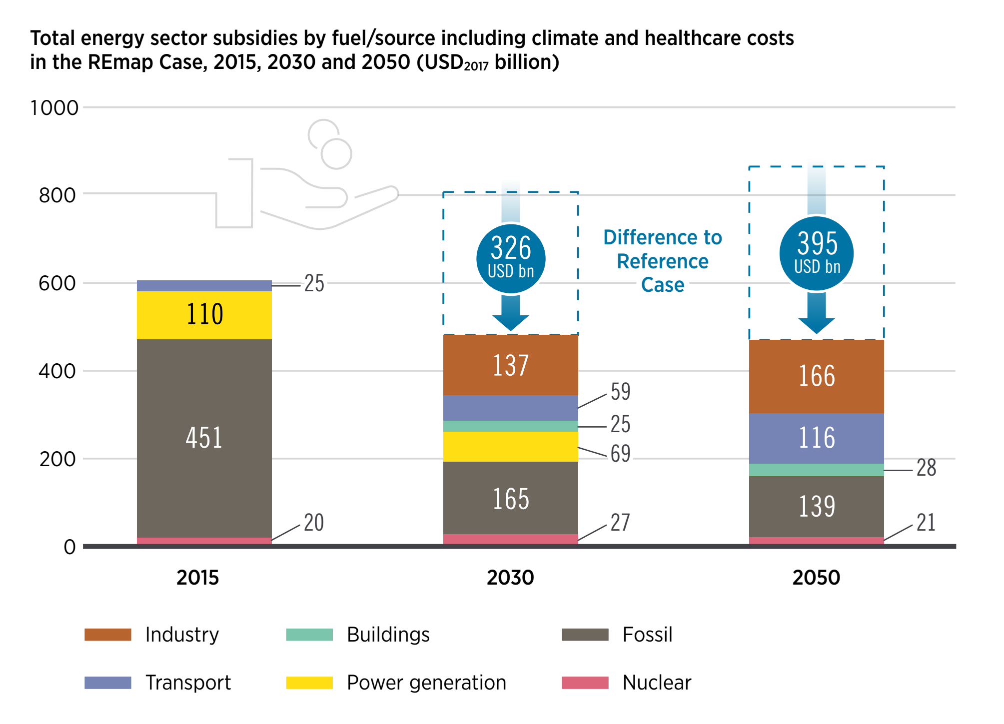
In 2015, total energy sector subsidies were estimated to be at least USD 606 billion, with subsidies to fossil fuels accounting for around 74% (USD 451 billion) of this total. Just over half of the subsidies to fossil fuel (USD 232 billion) supported oil production and use. Fossil fuels benefited to the tune of USD 106 billion as a result of support to electricity that increased fossil fuel use in generation, while natural gas production and use received around USD 98 billion in subsidies in 2015. Subsidies to renewable power generation were estimated at USD 110 billion in 2015. For renewable transport options (primarily biofuels in 2015) subsidies were estimated to be USD 25 billion.

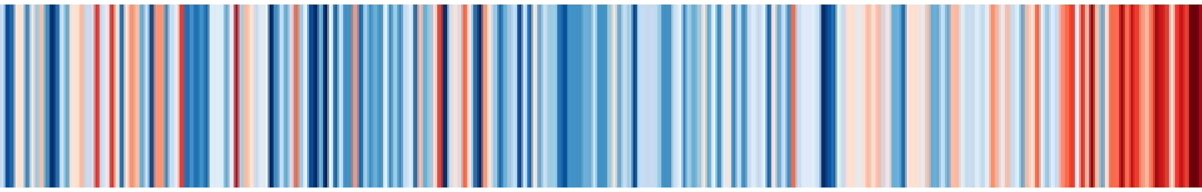
By 2030, total energy sector subsidies fall in the REmap Case to USD 481.5 billion, as fossil fuel subsidy reform reduces expenditures per unit of energy and as coal and oil demand falls below 2015 levels by 2030. Subsidies to renewables grow from USD 135 billion in 2015 to USD 208 billion in 2030 as the initial more costly efforts to decarbonise buildings and industrial energy use ramp up. Overall, however, total energy sector subsidies in 2030 are USD 325 billion lower than in the Reference Case, where fossil fuel demand continues to grow and little progress is made on fossil fuel subsidy reform. Between 2030 and 2050, additional efforts to decarbonise the energy sector result in subsidy needs for transport growing to USD 114 billion per year, notably as hydrogen and advanced biofuels are deployed at increasing scale. Energy efficiency is an important lever in decarbonising the energy sector and subsidies to energy efficiency (compared to the Reference Case) in industry grow, with USD 101 billion in 2050. Fossil fuel subsidies in 2050 will fall to USD 139 billion, 90% of which are attributable to CCS in industry, especially in the iron and steel and cement sectors.

Box 7. ENERGY SUBSIDIES (continued)

Overall, the REmap Case sees total energy sector subsidies that are USD 395 billion lower than in the Reference Case in 2050. However, this is before considering the implicit subsidy that fossil fuels derive from the unpriced externalities relating to air pollution and climate change costs. These are estimated to cost between USD 1 522 billion and USD 3 931 billion in 2050, even after the fossil fuel demand reductions in the REmap Case, and therefore dwarf the direct subsidies to fossil fuels, renewables and energy efficiency in 2050.

Figure 28. Total energy sector subsidies by fuel/source including climate and healthcare costs in the REmap Case, 2015, 2030 and 2050 (billion USD-2017)





Annual temperatures in Vienna from 1775-2017
The colour scale goes from 7.5°C (dark blue) to 12.0°C (dark red)

4 ENERGY-RELATED CO_2 EMISSIONS

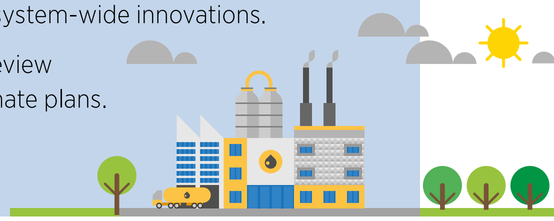
KEY FINDINGS:

Renewable power, combined with deep electrification of transport and heat, can deliver over 60% of the energy-related CO_2 emissions reductions needed for a Paris Agreement compatible energy pathway. If direct-uses of renewables are included, that share rises to 75%.

When including energy efficiency, combined with renewable energy and deep electrification of end uses, then the share increases to over 90% of the reductions in energy-related CO_2 emissions that are required.

Implications

- ***Adopt a holistic approach.*** Cutting energy-related CO_2 emissions needs to be addressed with a systems approach, which includes tapping into the synergies between energy efficiency and renewable energy, increasing the use of renewable electricity in all sectors and fostering system-wide innovations.
- ***Pair energy plans and climate plans.*** The G20 forum and the NDCs review are opportunities for further alignment between energy plans and climate plans.



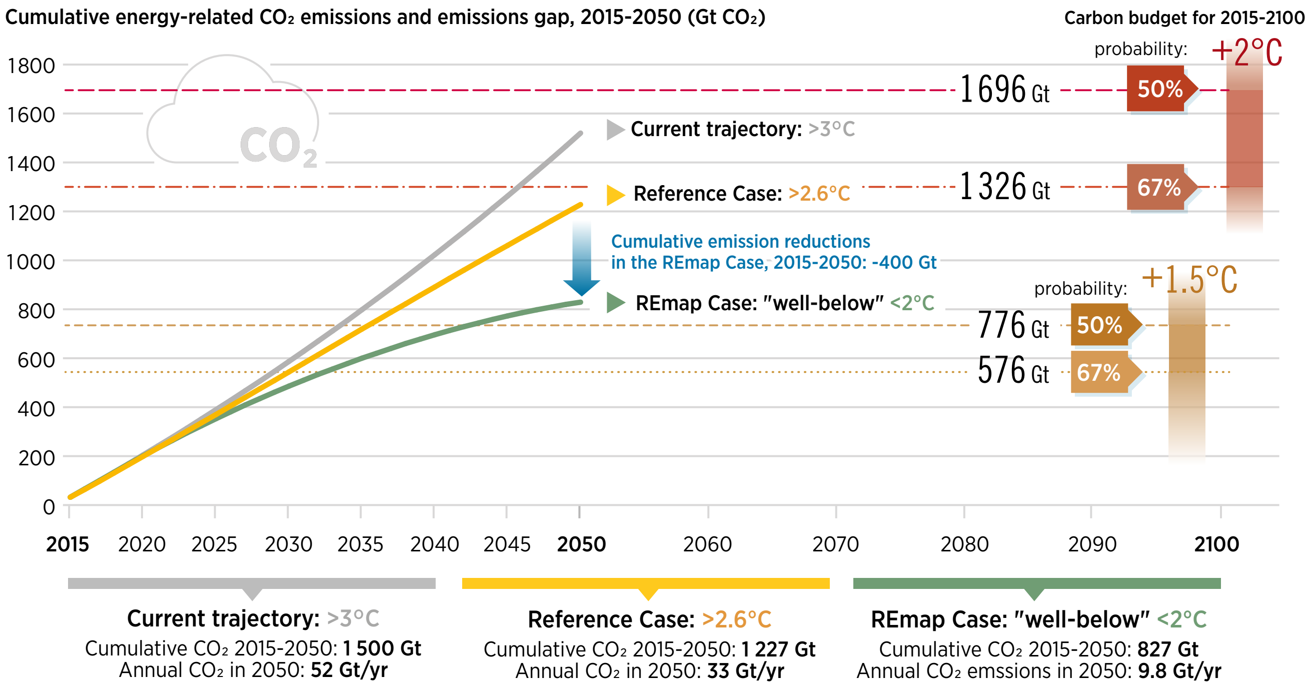
The reduction of energy-related CO_2 emissions is at the heart of the energy transition. Many governments have strengthened efforts to reduce national emissions in the last few years. The Reference Case analysed in this report, which considers current and planned policies (including NDCs), shows a projected fall in cumulative energy-related CO_2 emissions as a result of these revised policies and plans. Projected energy-related CO_2 emissions in the Reference Case by 2050 have declined from 1 380 Gt to 1 230 Gt between the 2017 and 2018 report, an 11% drop. But for this 2019 report, cumulative emissions are projected to be 1 227 Gt by 2050, which is effectively no change since the 2018 analysis. The annual emissions trend in the Reference Case is stagnant, at around 33-35 Gt of energy-related annual emissions annually in 2050, similar to today's level. If this Reference Case is followed, annual energy-related CO_2 emissions will decline only slightly by 2050, and will put the world on track for at least 2.6°C of warming after 2050.

However, recent trends have pointed to rising emissions, by around 1.4% in 2017 (IEA 2018a) and a bit below 2% in 2018 (Carbon Brief 2018). This shows that emissions in the last couple of years have risen on the order of 1-2% per year, and on average emissions have risen 1.3% per year over the last five years. If historical trends from the last five years continue, then that trend risks putting the world on a path to warming of 3°C or higher after 2050.

Government plans fall far short of the emissions reductions needed for a Paris compatible pathway. The Reference Case indicates that, under current and planned policies, the world will exhaust its energy-related CO_2 emissions budget in 10-18 years. To limit the global temperature increase to well below 2°C, cumulative emissions must be reduced by a further 400 Gt by 2050 (compared to current and planned policies, i.e. the Reference Case).

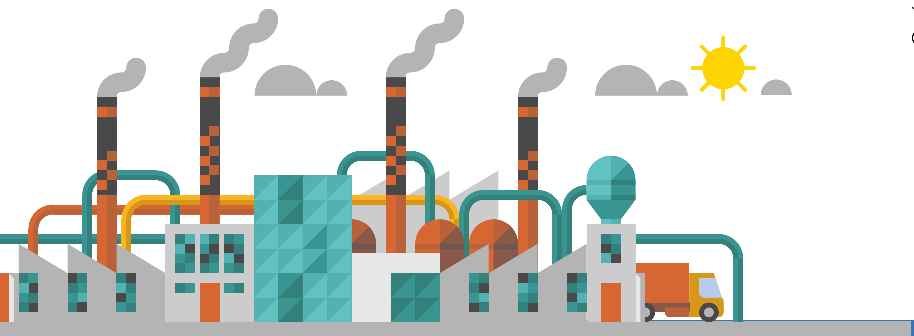
Figure 29. Following the current path, in 10-18 years the global energy-related CO_2 emissions budget to keep warming well below 2°C would be exhausted

Cumulative energy-related CO_2 emissions for the period 2015-2050 and emission budgets for 2015-2100 for 1.5°C and 2°C scenarios (Gt CO_2)



Notes: 1) Taking into account 2015-2017 emissions on top of the budget provided in IPCC (2018) (Table 2.2 – with no uncertainties and excluding additional Earth system feedbacks); 2) Budgets exclude industrial process emissions of 90 Gt; for this study, the assumption is that CO_2 emissions from land use, land-use change and forestry (LULUCF) fall from 3.3 Gt in 2015 to zero by mid-century. LULUCF subsequently becomes a net absorber of CO_2 over the remainder of the 21st century, and, as a result, cumulative CO_2 emissions from LULUCF between 2015 and 2100 are close to zero; 3) Current trajectory shows the recent historical trend line, assuming the continuation of the annual average growth in energy-related CO_2 emissions from the last five years (2013-2018) of 1.3% compound annual growth up to 2050; 4) Emissions budgets represent the total emissions that can be added into the atmosphere for the period 2015-2100 to stay below 2°C or 1.5°C at different confidence levels (50% or 67%) according to the IPCC (2018) report.

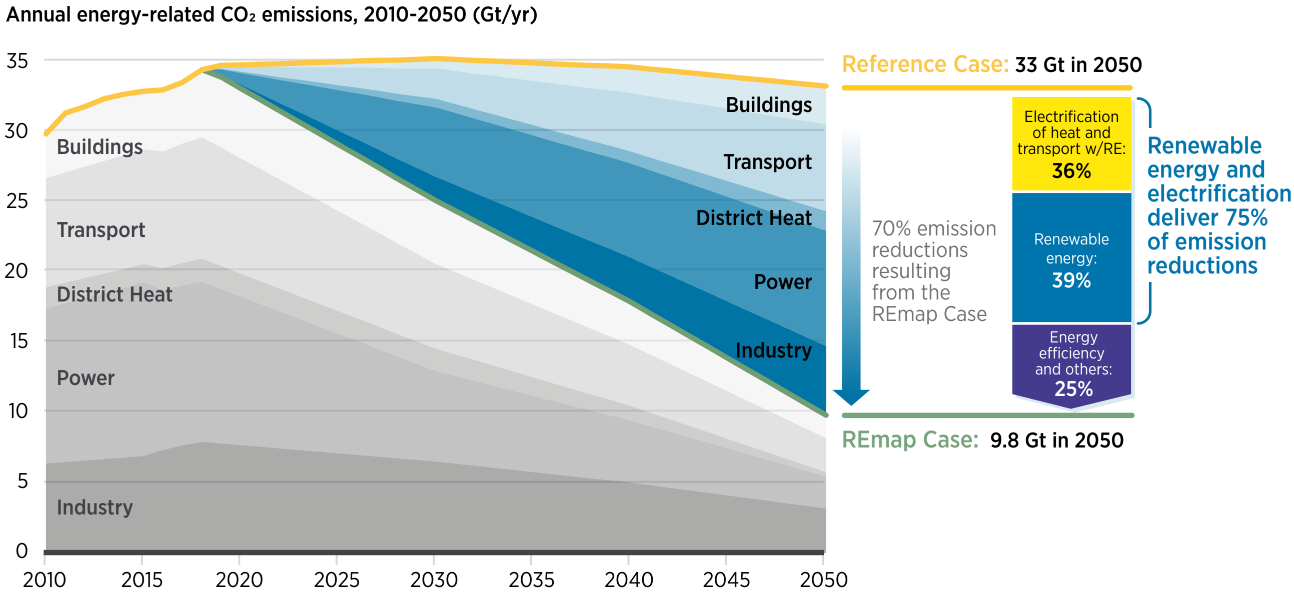
Energy-related CO_2 emissions projections, based on both historical trends and the Reference Case, remain far above what is needed to keep the rise in average global temperatures below a 2°C increase.



In the Reference Case, energy-related CO_2 emissions will increase slightly year-on-year to 2030, before dipping slightly by 2050 to just below today's level. However, significant additional reductions are needed. To meet a climate target of limiting warming to well below 2°C, annual energy-related CO_2 emissions still need to decline by 2050 from 33 Gt (in the Reference Case) to 9.8 Gt, a fall of more than 70%.

The REmap Case shows that the accelerated deployment of renewables, combined with deep electrification and increased energy efficiency, can achieve over 90% of the energy-related CO_2 emissions reductions needed by 2050 to set the world on a pathway to the well below 2°C aim of the Paris Agreement. Electrification with renewable power is key, together making up 60% of the mitigation potential; if the additional reductions from direct use of renewables are considered, the share increases to 75%; when adding energy efficiency, that share increases to over 90%. The remainder would be achieved by a mix of options including fossil fuel switching (to natural gas) and carbon capture and sequestration in industry. Nuclear power generation would remain at 2016 levels. Simultaneously, a significant effort would be required to reduce carbon emissions generated by industrial processes and by land use to less than zero by 2050. The climate goal cannot be reached without progress in those areas.

Figure 30. Renewable energy and energy efficiency can provide over 90% of the necessary reductions in energy-related CO_2 emissions



Note: "Renewables" implies deployment of renewable technologies in the power sector (wind, solar PV, *etc.*,) and end-use direct applications (solar thermal, geothermal, biomass). "Energy efficiency" contains efficiency measures deployed in end-use applications in industry, buildings and transport sectors (*e.g.,* improving insulation of buildings or installing more efficient appliances and equipment). "Electrification" denotes electrification of heat and transport applications, such as deploying heat pumps and EVs.

Annual energy-related CO_2 emissions under current and planned policies – the Reference Case – are expected to remain flat, at 33 Gt CO_2 in 2050. Yet they must be reduced by 70% to limit temperature rise to the well below 2°C climate goal.

In the REmap Case outlined in this report, renewable energy and energy efficiency measures, combined with deep electrification, provide over 90% of the reductions required by 2050.

The carbon intensity of the energy system declines in the Reference Case by around 20% by 2050. The largest decline is seen in the power sector, in which the carbon intensity is cut in half. The REmap Case accelerates this trend across the board, in which the power sector leads with a decline of 90% compared to 2016. The end-use sectors also see steep declines in the REmap Case, ranging from 50-60% in buildings and industry to 35% in transport. Overall, the carbon intensity of the energy system declines by 70% by 2050 in the REmap Case.

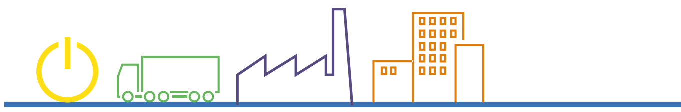
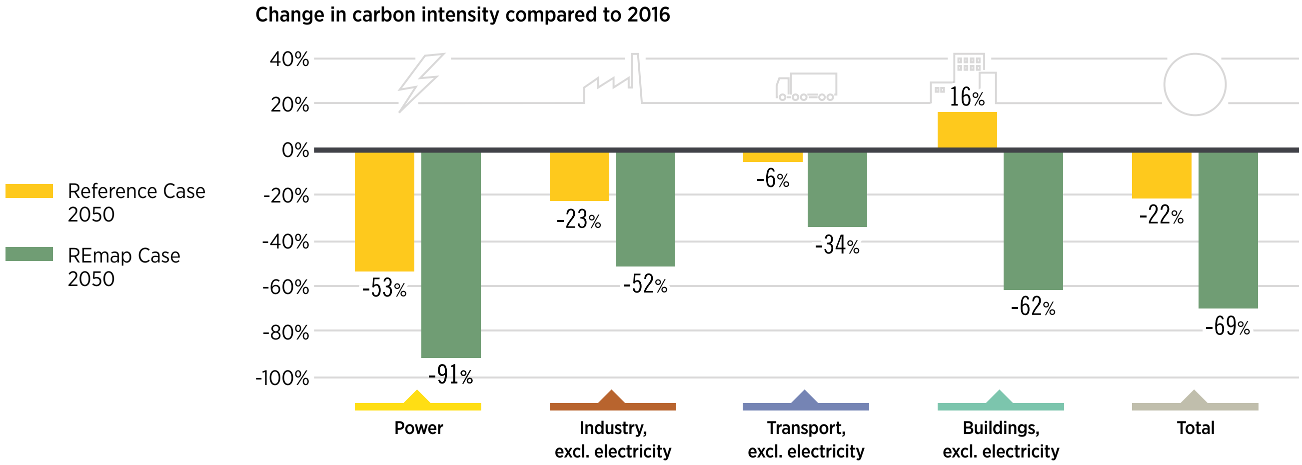
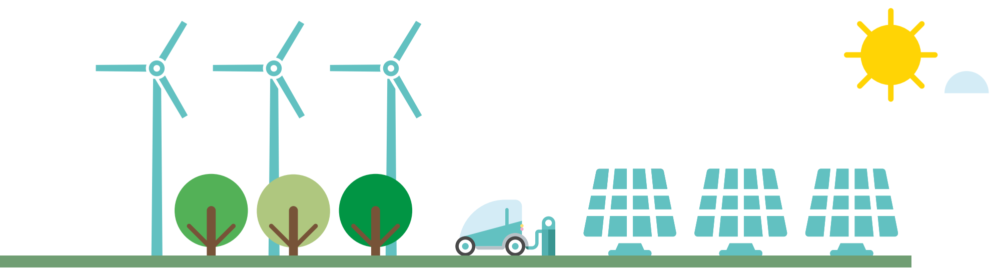


Figure 31. All sectors need to reduce carbon intensity over time

Change in carbon intensity compared to 2016 in Reference Case and REmap Case



Renewable energy, energy efficiency and electrification can reduce the carbon intensity of the energy system by 70% by 2050.



Box 8. TOWARDS ZERO CO_2 EMISSIONS: CASE STUDY FOR EUROPE

The REmap Case outlines a path towards emissions reductions of 70% by 2050. As the speed of emissions reductions will vary, some countries and regions will require further emissions reductions. Also, the effort that is needed for limiting warming to 1.5°C is still unclear, with some calling for zero CO_2 emissions globally by 2050. As 80% of emissions can be attributed to energy, this makes the energy transition an imperative.

"Zero emissions" means reducing energy-related emissions, process emissions and non-energy use emissions to zero, or compensating for any remaining emissions through land use, land-use change and forestry (LULUCF) efforts.

As part of the UNFCCC process, countries have to develop Long Term Scenarios for emissions reductions. Several have already been released (UNFCCC 2019).

The European Union has ambitious climate targets and has released *A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy* (EC 2018). Eight scenarios for 2050 are outlined and compared to a Baseline, five of which yield about 85-90% GHG emissions reductions and three of which yield 100% emissions reductions. The three scenarios vary in the extent of CCS, LULUCF deployment and reliance on technology vs. lifestyle changes.

In the Baseline (policies in place), GHG emissions are already reduced by 40% in 2030 and 62% in 2050, compared to 1990, largely due to existing energy efficiency and renewable energy policies. This leaves 1.6 Gt of energy CO_2 emissions left. These need to be reduced to the range of 0.005-0.2 Gt. The remaining CO_2 emissions and non-CO_2 emissions need to be compensated with up to 0.47 Gt of LULUCF.

Final energy demand is nearly halved compared to today, thanks to very ambitious efficiency policies and structural changes such as a circular economy.

Up to 0.39 Gt CO_2 is captured and used in the 1.5IIFE-LB scenario. CO_2 is captured from biomass plants (0.12 Gt/yr) and from the air (0.19 Gt). This CO_2 is used for geological storage (0.09 Gt), synthetic fuels (0.22 Gt) and synthetic materials (0.07 Gt). In the *1.TECH* scenario, biomass CCS doubles to more than 0.25 Gt.

The three scenarios assume strong electrification of end uses (around 50% excluding hydrogen, e-fuels and e-gas, or more than twice today's share). Electricity demand is 100-150% higher than it is today. Around 85% of electricity is generated from renewable sources. The scenarios also assume 15-18% bioenergy in final energy use, around 10% hydrogen and e-liquids each and 5-8% e-gas. Only 6-8% fossil fuel liquids and natural gas remain.

Synthetic fuels from CO_2 can replace fossil hydrocarbon fuels in the transport sector. Synthetic materials from biomass carbon and CO_2 are needed to replace petrochemical products.

Towards 2050, zero carbon steel and chemical industries are achieved, through a combination of a circular economy, hydrogen and biomass energy, and biomass feedstock. Hydrogen is used for steelmaking and other industrial processes.

All buildings are zero energy through high efficiency and building-integrated renewables.

In the transport sector, freight, air and shipping are also decarbonised through a mix of electrification, biofuels, synthetic fuels and hydrogen. Smart and sustainable city and infrastructure planning is ubiquitous.

Based on these scenarios, several research focus areas around transformational carbon-neutral solutions are evident. These include deep electrification, with emphasis on high renewable penetration, subsequent smart networks and the important role of batteries (including EV batteries). They also include technologies such as hydrogen and fuel cells, energy storage and methods that include carbon-neutral transformation of energy-intensive industries (materials, processes and feedstocks). Other necessary steps are growth in the circular economy, including consumer actions, and in the bio-economy, and sustainably intensifying agriculture and forestry.

5 COUNTRY AND REGIONAL INSIGHTS

KEY FINDINGS:

In the REmap Case, energy use is flat to 2050 in Europe, Middle East and North Africa (MENA), and North America while some sustained growth can be found in the other regions, such as in Latin America, Oceania, sub-Saharan Africa and Southeast Asia.

By 2030 in the REmap Case, Europe and North America have the largest emissions reductions relative to 2016 levels, with 45% and 37% respectively. However, on a 2050 horizon, East Asia also would see a significant reduction (80%), in addition to North America and Europe (78% and 81%, respectively).

Electrification will have varying growth trends in the regions. By 2050 in the REmap Case, the highest share of electricity consumption is reached in East Asia, being 58%, while lower shares (below the global average) are found in Latin America and the Rest of Europe (non-EU).

According to the REmap Case, the highest level of investments in renewable energy between 2016 and 2050 will happen in East Asia with USD 25 trillion, followed by North America with USD 16 trillion. Sub-Saharan Africa and Oceania will have the lowest investment amounts, with USD 3 trillion and USD 1 trillion, respectively.

Implications:

- ***Strengthen regional approaches.*** Countries in the same region often share the same environmental and energy endowments and face similar challenges. As such they could benefit from stronger collaborations, such as exploring possibilities and ways of developing regional energy markets as a means of promoting security of supply.
- ***Foster collaboration among regional organisations.*** Exchanges across borders through regional organisations (EU, ASEAN, APEC, etc.) are a means of supporting knowledge transfer and replication of good practices.

This study included regional perspectives for 10 regions. These include East Asia, Rest of Asia, the European Union, Rest of Europe, Latin America, Middle East and North Africa (MENA), North America, Oceania, sub-Saharan Africa, and South-east Asia. There are large differences between these regions and their current energy situations, but similar trends occur in the REmap Case.

Looking into regional findings, there are some trends that can be identified. In terms of energy demand growth, while energy use does not increase by 2050 in Europe, the MENA region and North America, the other regions observe some growth.

Electrification, which is at the core of the energy transformation outlined in the REmap Case, will have varying growth trends in the regions. Electricity consumption in final energy use reaches the highest share in East Asia, being 58% by 2050, with China at the forefront of the region at 61%. The lower shares occur in Latin America and the Rest of Europe, at just around 38%, below the global average of 49%.

Hand in hand with the electrification of energy applications, wind and solar power play key roles in the energy transformation. By 2050, the biggest wind and PV markets will be North America and East Asia, with a high concentration of deployment in the latter in China.

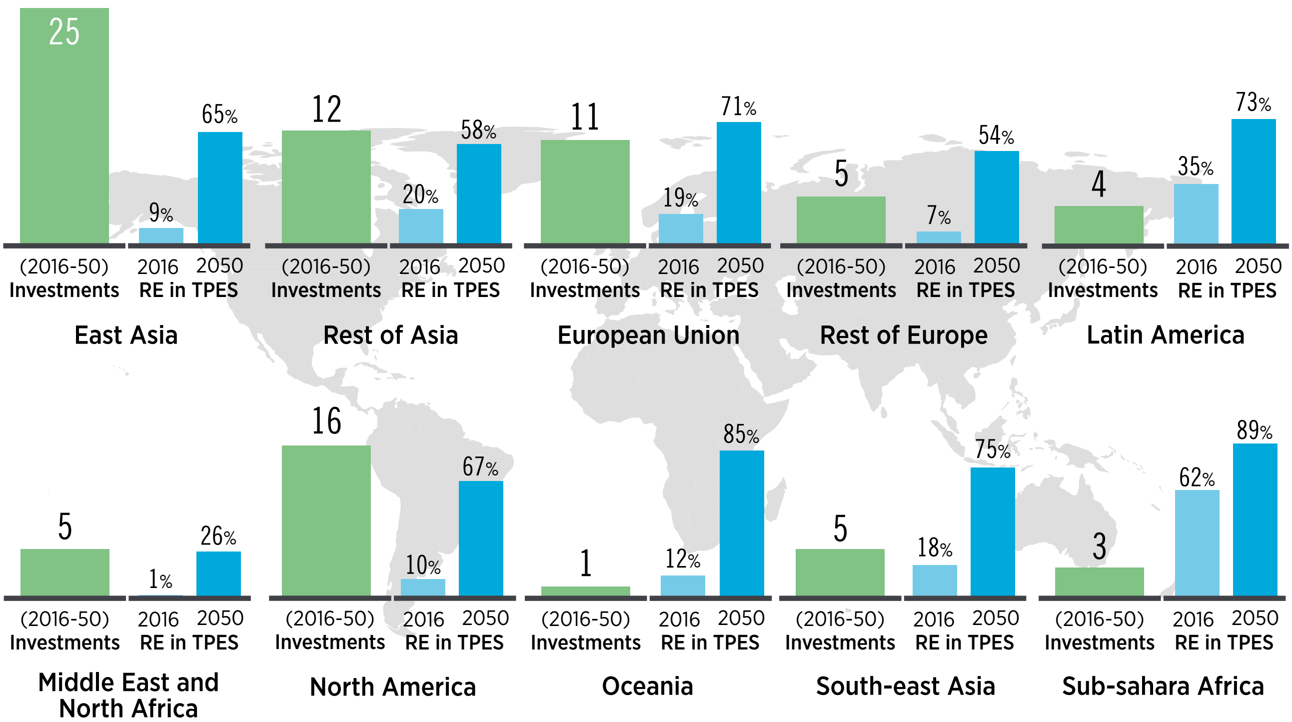
The regions with the largest emissions reductions relative to 2016 levels by 2030 are the European Union and North America, continuing until 2050, East Asia also achieves significant reductions. When comparing emissions reductions between the Reference Case and the REmap Case in 2050, then the picture is a bit different. North America is the region with the largest annual reduction potential of 5.3 Gt in 2050 (led by the United States), followed by the Rest of Asia with 5.2 Gt (led by India), East Asia (led by China) with 3.1 Gt, and MENA with 2.1 Gt. This analysis shows where the most additional reduction potential exists beyond national plans, but is not necessarily correlated to 2016 emissions levels. This explains why Europe has such low additional potential in the REmap Case (meaning their Reference Case is already quite ambitious).(See Figure 31, page 78)

The highest shares of renewable energy in primary energy supply in 2050 will be reached in sub-Saharan Africa and Oceania, with levels way above 80%, followed by Latin America and the EU at above 70%. In contrast, the MENA region has the lowest share with just 26%.

In order to realise the proposed levels of renewable energy deployment in the REmap Case, investments in renewable energy vary greatly among regions and are not necessarily correlated with the share of renewable energy, due the size of the energy systems, different resource endowments and differing starting points. **The highest level of investments in renewable energy between 2016 and 2050 will be seen in East Asia with USD 25 trillion, followed by North America with USD 16 trillion. Sub-Saharan Africa and Oceania will have the lowest investment amounts, with USD 3 trillion and USD 1 trillion, respectively.**

Figure 32. Investments are widespread around the world

Low carbon technology investments over 2016-2050 (USD trillions) and RE shares in TPES (%)



The renewables share in the energy mix will need to increase in all regions up to 2050. Sub-Saharan Africa (89%), Oceania (85%), South-East Asia (75%) and Latin-America (73%) and Europe (71%) will see the highest share, with all above 70% of renewables in the energy supply. East Asia and North America will, however, require almost 50% of the total energy investment over the period in the REmap Case due to increasing energy demand.

Figure 33. Regional key indicators infographic

			NORTH AMERICA			LATIN AMERICA		
				REmap			REmap	
			2016	2030	2050	2016	2030	2050
Energy use	TPES	EJ/yr	113	90	82	27	30	33
	TFEC	EJ/yr	82	69	58	22	22	21
RE shares	RE share in TFEC	%	10%	29%	68%	29%	47%	67%
	RE share in TPES	%	10%	30%	67%	31%	53%	73%
	RE share in power generation	%	22%	60%	85%	63%	85%	93%
Electri-fication	Share of electricity use in TFEC	%	20%	28%	52%	18%	26%	39%
	Share of electricity use in Industry	%	20%	21%	29%	22%	27%	33%
	Share of electricity use in Transport	%	0%	13%	57%	0%	9%	24%
	Share of electricity use in Buildings	%	48%	54%	78%	44%	61%	78%
Power capacity	Wind	GW	100	448	1 314	15	93	188
	Solar PV	GW	38	485	1 728	3	108	281
Emissions	Energy-related CO_2 emissions	Mt CO_2/yr	6 632	3 653	1 435	1 234	951	551
	Avoided emissions (vs Ref Case)	Mt CO_2/yr	-	– 2 925	– 5 369	-	– 484	– 1 124
	Reduction relative to 2016	%		– 45%	– 78%		– 23%	– 55%

			SUB-SAHARA AFRICA			OCEANIA		
				REmap			REmap	
			2016	2030	2050	2016	2030	2050
Energy use	TPES	EJ/yr	25	13	35	7	9	12
	TFEC	EJ/yr	21	9	26	4	6	5
RE shares	RE share in TFEC	%	8%	42%	86%	12%	26%	75%
	RE share in TPES	%	7%	43%	89%	11%	39%	85%
	RE share in power generation	%	25%	67%	95%	23%	66%	93%
Electri-fication	Share of electricity use in TFEC	%	6%	23%	48%	23%	22%	45%
	Share of electricity use in Industry	%	23%	31%	29%	28%	20%	67%
	Share of electricity use in Transport	%	0%	2%	47%	1%	6%	31%
	Share of electricity use in Buildings	%	4%	57%	89%	57%	64%	34%
Power capacity	Wind	GW	2	33	314	5	25	65
	Solar PV	GW	3	79	548	5	27	109
Emissions	Energy-related CO_2 emissions	Mt CO_2/yr	756	587	311	438	409	122
	Avoided emissions (vs Ref Case)	Mt CO_2/yr	-	-231	-658	-	-178	-487
	Reduction relative to 2016	%		-22%	-59%		-7%	-72%

EU28

	REmap	
2016	2030	2050
63	54	45
44	38	29
17%	30%	70%
16%	31%	71%
30%	55%	86%
23%	30%	49%
33%	40%	54%
2%	7%	32%
33%	42%	55%
154	319	621
101	284	784
3 050	1 920	610
-	-711	-1 337
	-37%	-80%

REST OF EUROPE

	REmap	
2016	2030	2050
39	38	33
23	23	18
7%	20%	61%
6%	19%	54%
27%	42%	82%
17%	23%	38%
25%	34%	44%
7%	12%	37%
22%	28%	42%
2	33	79
2	39	107
2 074	1 639	655
-	-740	-1 631
	-21%	-68%

MENA

	REmap	
2016	2030	2050
39	39	30
25	25	20
2%	8%	26%
1%	9%	26%
3%	27%	53%
17%	20%	38%
11%	12%	20%
0%	2%	15%
41%	48%	77%
2	76	212
2	66	147
2 375	2 000	1 090
-	-888	-2 160
	-16%	-54%

SOUTHEAST ASIA

	REmap	
2016	2030	2050
24	39	54
17	21	28
10%	27%	68%
13%	41%	75%
20%	53%	85%
18%	20%	42%
22%	16%	27%
0%	3%	23%
29%	63%	91%
1	13	32
4	106	647
1 365	1 632	767
-	-412	-2 151
	20%	-44%

EAST ASIA

	REmap	
2016	2030	2050
157	166	129
101	105	89
8%	31%	70%
7%	27%	65%
22%	60%	90%
24%	37%	58%
30%	42%	66%
3%	14%	46%
32%	45%	57%
153	1 263	2 696
124	1 644	3 118
11 158	8 360	2 225
-	-1 895	-3 148
	-25%	-80%

REST OF ASIA

	REmap	
2016	2030	2050
61	77	86
41	51	55
9%	24%	59%
8%	27%	58%
19%	52%	81%
18%	26%	47%
22%	20%	32%
1%	18%	51%
20%	51%	75%
40	223	541
15	314	1 072
3 602	3 801	2 003
-	-1 600	-5 237
	6%	-44%

6 SCENARIO COMPARISON

KEY MESSAGES:

An analysis of energy scenarios shows that there is an increasing consensus on the important role that renewable power will play in the energy mix in the coming decades.

However, opinions differ regarding the level of electrification in end-use sectors, as well as the level of reduction of CO_2 emissions, and the level of energy demand.

The findings of the REmap analysis outlined in this report can be compared with energy scenarios from other major studies. This section compares the REmap analysis with the following scenarios:

- **Shell – Sky Scenario** (Shell 2018)
- **Equinor – Renewal (Equ-Ren.)** (Equinor 2018)
- **McKinsey – Reference Scenario (McK.)** (McKinsey & Company 2019)
- **DNV-GL – Energy Transition Outlook** (DNV GL 2018)
- **IPCC - Below 1.5°C and 1.5°C high** (IPCC 2018)
- **Sven Teske – Achieving the Paris Climate Agreement Goals** (Teske 2019)
- **BNEF – New Energy Outlook** (Bloomberg 2018)
- **IEA – World Energy Outlook, Sustainable Development Scenario** (WEO-SDS) (IEA 2018g)
- **British Petroleum (BP) – Rapid Transition Scenario (BP-RT)** (BP 2019)
- **ExxonMobil – Outlook for Energy (EXX.)** (ExxonMobil 2018)

Table 3. Comparison of scenarios for the global energy transition (2040 and 2050)

2040		1.5 degrees		2 degrees	BAU
	Ref. Case	REmap Case	IEA- WEO SDS	EXX.	BP- RT
TPES (EJ/yr)	685	553	574	n/a	n/a
RE in TPES	22%	47%	31%	16%	38%
RE in TPES (EJ/yr)	151	260	178	n/a	n/a
TFEC (EJ/yr)	459	367	417	718	686[b]
Electrification in TFEC	27%	38%	28%	n/a	n/a
RE in the power sector	62%	75%	63%	20%	51%
Emissions in 2050 (Gt CO_2/yr)	34	17	18	37	18
Nuclear in power generation	9%	6%	13%	17%	n/a
Modern biomass (TPES) (EJ/yr)	64	101	63	n/a	n/a

Notes: (a) Total Final consumption (i.e. including non-energy uses); (b) Primary Energy Consumption; (c) Final Energy Demand; (d) Primary Energy Demand; (e) Only power sector; (b) Values in green are close to the REmap Case (within a 15% margin) and those in red differ by a larger margin (over 30% gap).

Many scenarios show findings that are similar to the REmap Case. They show that the increased decarbonisation of the energy system is driven largely by renewable energy and energy efficiency. There is an increasing consensus on the important role of renewable power, which for most of the scenarios is above 70% in 2050 (compared to around 26% today), as well as on the role of increasing the share of electricity consumed in final energy consumption. Similarly, some of the scenarios agree with the REmap analysis on the absolute renewable energy levels in TPES or TFEC of around two-thirds by 2050.

A comparison analysis also shows a correlation between energy demand, energy efficiency and share of renewable energy and the scenarios with high renewable energy shares are also the ones with high efficiency. The comparison also suggests that the goal of the limiting temperature increase to well below 2°C would be most achievable with lower overall energy demand (TPES), while achieving the 1.5°C target would also require significant structural and lifestyle changes.

However, despite the similarities, differences can also be found in the scenarios in aspects such as the level of electrification in end-use sectors and reductions in CO_2 emissions. The divergence in results can be mainly explained by the different objectives behind the scenarios. For many, the analysis is defined by the need to reduce energy-related CO_2 emissions to limit the temperature increase to between 2°C and 1.5°C. Others have modelled the energy system in a more conservative (business-as-usual) way.

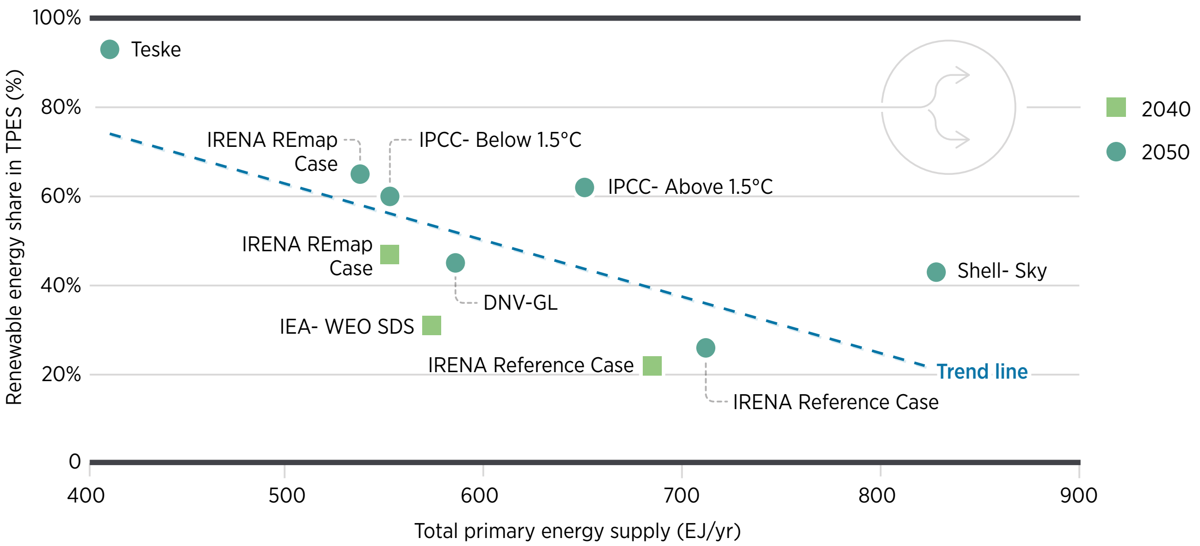
2050

		BAU	1.5 degrees					2 degrees		Unclassified
	Ref. Case	McK.	REmap Case	Shell-Sky	IPCC-<1.5°C	IPCC->1.5°C	Teske	Equ-Ren.	DNV-GL	BNEF
TPES (EJ/yr)	712	650	538	828	553	651	412[d]	n/a	586	n/a
RE in TPES	26%	n/a	65%	43%	60%	62%	93%	40%	45%	n/a
RE in TPES (EJ/yr)	185	n/a	350	356	333	405	383	n/a	259	n/a
TFEC (EJ/yr)	479	700	351	449[a]	n/a	n/a	253c	535	450	n/a
Electrification in TFEC	30%	29%	49%	44%	n/a	n/a	n/a	33%	45%	n/a
RE in the power sector	69%	54%	86%	74%	77%	82%	100%	74%	81%	64%
Emissions in 2050 (Gt CO_2/yr)	33	32.8	9.8	18	<8	14	~0	12.6	20	8.5[e]
Nuclear in power generation	9%	4%	5%	10%	8%	11%	0%	11%	4%	7%
Modern biomass (TPES) (EJ/yr)	70	n/a	125	67	152	160	n/a	n/a	67	n/a

Figure 34. There is a correlation between renewable energy share and energy demand

Renewable energy share in TPES (%) and TPES (EJ)

Renewable energy and total primary energy supply (TPES) in different scenarios in 2040 and 2050



Source: Shell – Sky Scenario (Shell, 2018), IPCC – Below 1.5 °C and above (IPCC, 2018), IEA – World Energy Outlook Sustainable Development Scenario (WEO-SDS) (IEA, 2018d), DNV-GL (DNV GL, 2018) and Sven Teske – Achieving the Paris Climate Agreement Goals (Teske, 2019)

Scenarios with higher renewable energy shares also have higher energy efficiency, resulting in lower overall energy demand and emissions.

The **IEA states that its SDS** scenario puts forward an integrated approach for achieving the three most important energy-related Sustainable Development Goals: achieving universal energy access, reducing CO_2 emissions in line with the Paris Agreement and reducing the severe health impacts of air pollution. The IEA SDS scenario assumes that non-economic barriers to electric technologies are minimised and that electricity progressively increases its role in the energy system, representing 28% of total final consumption, and that 63% of electricity generation is renewable by 2040. The buildings sector realises the highest level of electrification, followed by industry and transport (14%). The results from the IRENA and IEA scenarios have some similarities, and both recognise that for the energy transition to happen, strong policies and commitments by governments and society as a whole will be needed to accelerate the current pace. However, IRENA considers renewable energy to have greater potential than the IEA does, and renewable energy consequently brings higher emissions reductions in the IRENA REmap Case.

The **Shell Sky scenario** is less ambitious in terms of emissions reductions until 2050 and assumes negative emissions post-2050. However, it also foresees 43% of renewable energy in TPES in 2050. While that is lower than the 65% in the IRENA REmap Case, it suggests a similar level of renewable energy in absolute terms given the higher total primary energy supply (828 EJ) in the Shell scenario. Sky sees electrification as one of the most important energy system trends. Under the Sky scenario, the role of electricity as an energy carrier would grow very quickly across the economy, reaching 44% of total final energy consumption in 2050. Compared to historical electrification trends, the electricity share would grow three times faster in the coming decades to reach the level envisioned in this scenario by 2050.

The **Equinor Renewal scenario** represents a future trajectory for the energy markets that is policy driven, characterised by global cooperation with the aim of a fast transition of the energy system to meet the well below 2°C target of the Paris Agreement. In the Renewal scenario, renewable electricity is key, reaching 74% of electricity generation by 2050. The transport sector would see a massive change towards electricity. The light-duty sector would be clearly dominated by electric vehicles, and half of the truck fleet would be either hybrid or electric. Although electrification is also a key driver towards a decarbonised system in buildings and industry, in these two sectors the transition is slower in Equinor's scenario than in the REmap Case.

The 2019 **McKinsey** scenario sees electrification playing a role in the analysis, with electricity demand doubling by 2050 driven by increased demand in buildings and in road transport. Renewables are projected to make up over 54% of generation, with solar and wind rapidly gaining importance and growing. Emissions remaining flat, therefore the goal of limiting warming to 1.5°C or even a 2oC in this scenario would remain unlikely, though the scenario is defined as a "Reference Case" scenario and not one focused on attaining climate goals.

DNV-GL forecasts a decline in energy demand compared to today's levels and a rise of renewables in the energy mix. The scenario forecasts strong electrification of all sectors, especially in the transport sector, as well as very high shares of renewables in the power sector (81%). Yet the emissions reductions are 17.5 Gt/yr, which is not as ambitious as in other scenarios.

The **IPCC High 1.5-degrees** scenario has some similarities with the IRENA REmap Case, but the REmap Case has slightly higher shares of renewable energy in total primary energy supply and in the power sector. Emissions in the IPCC High 1.5-degrees scenario are 13.8 Gt/yr in 2050, which is higher than both the IRENA REmap Case (9.8 Gt/yr) and the IPCC Below 1.5-degrees (8 Gt/yr).

The **Teske 1.5-degrees** scenario is based on the achievement of 100% renewable energy and emissions close to zero Gt/yr by 2050 in order to meet the goals of the Paris Agreement. Global electricity demand is forecasted to increase due to the electrification of the transport and heating sectors, and renewable electricity will reach 100% of generation by 2050, with "new" renewables (i.e. wind, solar and geothermal) representing more than 83% of the total electricity generated.

BNEF New Energy Outlook scenario is the company's annual forecast of the world's power sector. Renewables are forecasted to dominate the generation mix by 2050, representing almost two-thirds of power generation, including 50% from wind and solar. Solar and wind will see large deployment due to declining costs, which they project will drop by 71% and 58% respectively. With more renewables on the grid, BNEF foresees batteries playing an essential role for load balancing. The falling costs of batteries will make this support possible on a widespread scale. However, while renewables are foreseen to be dominating the generation mix, gas will remain an integral part of the landscape.

BP's Rapid Transition scenario foresees an increase in energy demand as a necessity for rising prosperity. The share of renewable energy in primary energy increases to 38%, and in the power sector to 51%. Natural gas grows consistently and becomes the second largest source after renewables.

Exxon provides its first 2°C "scenario" analysis. According to the analysis, in 2040, energy supply will still be majority supplied by oil and natural gas, supplying about 55% of the world's energy needs. Oil will still provide the largest share of the energy mix, with demand rising about 20%. The share of renewable energy in primary energy will be 16%, slightly above today's level, and the share of electricity generated by renewables is expected to only be 20% in 2040, lower than the level today.

Box 9. INSTITUTIONS IRENA USED TO SUPPORT THE ANALYSIS IN THIS REPORT

In addition to analysis done by IRENA for this report, there were many external studies, datasets and other information that was used to inform the analysis for G20 countries which forms the basis of the analytical findings of this report. The following table lists some of the key institutions from which this information was sourced.

Table 4. List of select countries and institutions

JURISDICTION	INSTITUTION
Argentina	Ministry of Energy and Mining (MINEM)
Australia	University of Sydney and Institute for Sustainable Futures (ISF)
Brazil	Ministry of Mines and Energy (MME) and The Energy Research Office (EPE)
Canada	Natural Resource Canada and Energy Super Modelers and International Analysts (ESMIA)
China	China National Renewable Energy Centre (CNREC)
European Union	European Commission, Directorate-General for Energy
France	Agency for the Environment and Energy Management (ADEME)
Germany	Federal Ministry for Economic Affairs and Energy (BMWi)
Japan	Ministry of Economy, Trade and Industry (METI)
India	National Institution for Transforming India (NITI Aayog), Central Electricity Authority (CEA), Alliance for an Energy Efficient Economy (AEEE), Council on Energy, Environment and Water (CEEW), The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ)
Italy	Ministry for Environment, Land and Sea Protection (MATTM) and Terna
Mexico	Mexican Energy Secretariat (SENER), Mexican Energy Control Centre (CENACE), Mexican National Commission for the Efficient Use of Energy (CONUEE) and Enerdata
Republic of Korea	Ministry of Foreign Affairs (MOFA) and Korea Energy Economics Institute (KEEI)
UK	Department for Business, Energy and Industrial Strategy
USA	Energy Information Administration (EIA) and National Renewable Energy Laboratory (NREL)

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