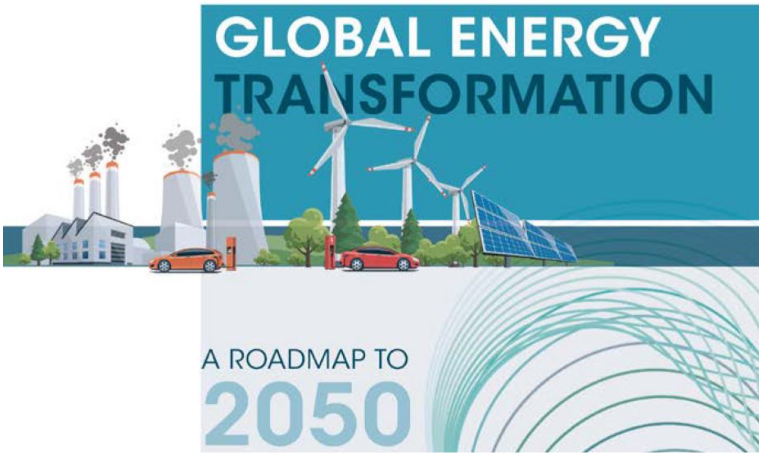
Global Energy Transformation Path to 2050



10

Professional Development Hours (PDH) or
Continuing Education Hours (CE)
Online PDH or CE course

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ABBREVIATIONS

°C	degrees Celsius
CCS	carbon capture and storage
CHP	combined heat and power carbon
CO_2	dioxide
CPI	Climate Policy Institute
CSP	concentrated solar powerexajoule
EJ	European Union
EU	electric vehicle
EV	Group of Twenty
G20	gross domestic product
GDP	greenhouse gas gigaton
GHG	gigawatt gigawatt
Gt	thermal
GW	information and
GWth	communicating technologies
ICT	International Energy Agency
	including
IEA	International Renewable
incl.	Energy Agency kilometre
IRENA	kilowatt-hour
	Lawrence Berkeley National Laboratory
km	square metre
kWh	metre cubed
LBN	megajoules not
L	applicable
m^2	Nationally Determined
m^3	Contributions
M	Organization of the PetroleumExporting
J	Countries
N/A	petajoule
NDCs	photovoltaic
	research and development research,
OPE	development, anddemonstration
	renewable energy roadmap
CPJ	Sustainable Development Goals
PV	
R&D	
RD&	
D	
REmap	
SE4ALL	Sustainable Energy for All
T&D	transmission and distribution
TFEC	total final energy consumption
TPES	total primary energy supply TWh
	terawatt-hour
UN	the United Nations
USA	United States of America
USD	United States Dollar
VRE	variable renewable energyyr
	year

EXECUTIVE SUMMARY

Renewable energy needs to be scaled up at least six times faster for the world to start to meet the goals set out in the Paris Agreement.

The historic climate accord from 2015 seeks, at minimum, to limit average global temperature rise to "well below 2°C" in the present century, compared to pre-industrial levels. Renewables, in combination with rapidly improving energy efficiency, form the cornerstone of a viable climate solution.

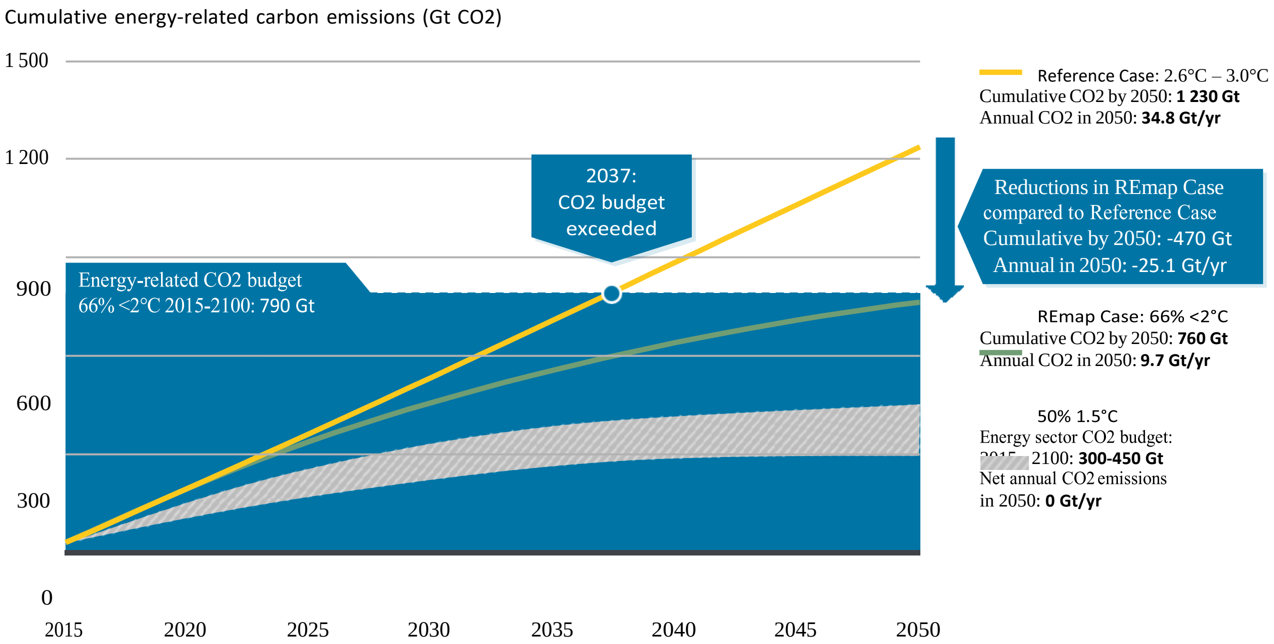
Keeping the global temperature rise below 2 degrees Celsius (°C) is technically feasible. It would also be more economically, socially and environmentally beneficial than the path resulting from current plans and policies. However, the global energy system must undergo a profound transformation, from one largely based on fossil fuels to one that enhances efficiencyand is based on renewable energy. Such a global energy transformation – seen as the culmination of the "energy transition" that is already happening in many countries – can create a world that is more prosperous and inclusive.

Currently, emission trends are not on track to meet that goal. Government plans still fall far short of emission reduction needs. Under current and planned policies, the world would exhaust its energy-related "carbon budget" (CO_2) in under 20 years to keep the global temperate rise to well below 2°C (with 66% probability), while fossil fuels such as oil, natural gas and coal would continueto dominate the global energy mix for decades to come.

To meet the below 2°C goal, immediate action will be crucial. Cumulative emissions must at least be reduced by a further 470 gigatons (Gt) by 2050 compared to current and planned policies (business-as-usual) to meet that goal.

Figure ES1. In under 20 years, the global energy-related CO_2 emissions budget to keep warming below 2°C would be exhausted

Cumulative energy-related CO_2 emissions and emissions gap, 2015-2050 (Gt CO_2)



Energy efficiency and renewable energy are the main pillars of the energy transition. While different paths can mitigate climate change, renewable energy and energy efficiency provide the optimal pathway to deliver the majority of the emission cuts needed at the necessary speed.Together they can provide over 90% of the energy-related CO_2 emission reductions that are required, using technologies that are safe, reliable, affordable and widely available.

Renewable energy and energy efficiency need to expand in all sectors. The total share of renewable energy must rise from around 15% of the total primary energy supply (TPES) in 2015 to around two-thirds by 2050. To meet climate targets, the energy intensity of the global economywill need to fall by about two-thirds by 2050, lowering the total primary energy supply in that year to slightly less than 2015 levels. This can be achieved, despite significant population and economic growth, by substantially improving energy efficiency.

By 2050, all countries can substantially increase the proportion of renewable energy in their total energy use. REmap, a global roadmap prepared by the International Renewable Energy Agency (IRENA), suggests that renewables can make up 60% or more of many countries' total finalenergy consumption (TFEC). For instance, China could increase the share of renewable energy in its energy use from 7% in 2015 to 67% in 2050. In the European Union (EU), the share could grow from about 17% to over 70%. India and the United States could see shares increase to two-thirds or more.

A decarbonised power sector, dominated by renewable sources, is at the core of the transition to a sustainable energy future. The share of renewable energy in the power sector would increase from 25% in 2017 to 85% by 2050, mostly through growth in solar and wind power generation. This transformation would require new approaches to power system planning, system and market operations, and regulation and public policy. As low-carbon electricity becomes the main energy carrier, the share of electricity consumed in end-use sectors would need to double from approximately 20% in 2015 to 40% in 2050. Electric vehicles (EVs) and heat pumps would become more common in most parts of the world. In terms of final energy, renewable electricity would provide just under 60% of total renewable energy use, two and a half times its contribution to overall renewable energy consumption today.

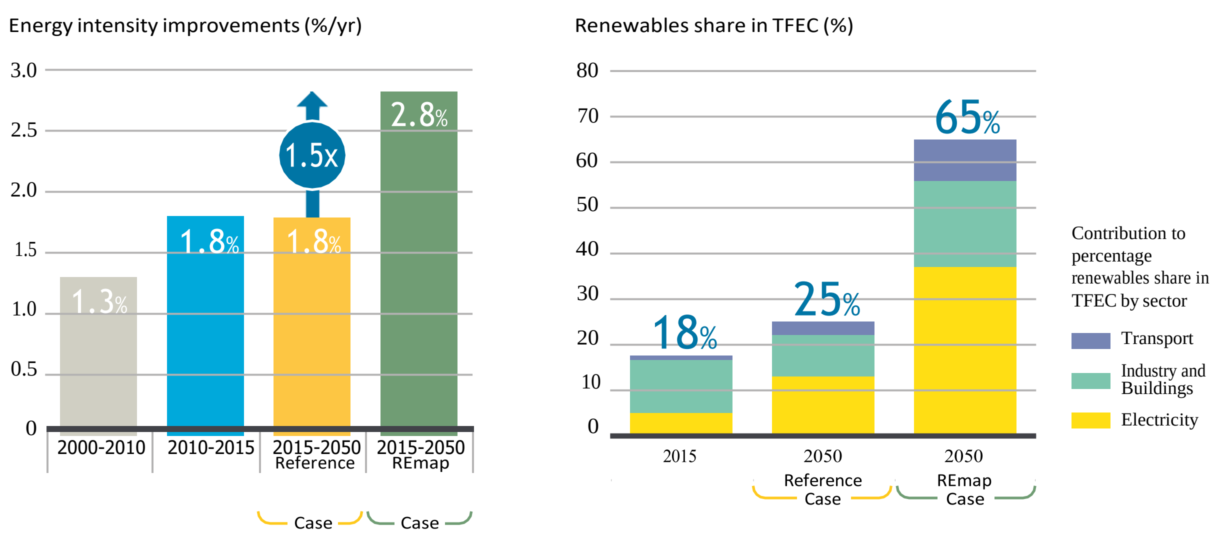
The power sector has made significant progress in recent years, but the speed of progress must be accelerated. In 2017 the power sector added 167 gigawatts (GW) of renewable energy capacity globally, a robust growth of 8.3% over the previous year and a continuation of previous growth rates since 2010 averaging 8% per year. Renewable power generation accounted for an estimated quarter of total global power generation, a new record. New records were also set for solar and wind installation, with additions of 94 GW in solar photovoltaic (PV) and 47 GW wind power, including 4 GW of offshore wind power. Renewable power generation costs continue to fall. There is ample evidence that power systems dominated by renewables can be a reality, so the scale and speed of renewable energy deployment can be accelerated with confidence.

Industry, transport and the building sectors will need to use more renewable energy. In these sectors, renewable sources including increased renewable electricity supply, but also solar thermal, geothermal energy and bioenergy, must play important roles. Renewable electricity will play an increasingly important role but a large contribution are renewable fuels and direct-uses that are needed for heat and transport. For these the use of biomass could provide a little under two-thirds of renewable energy used for heat and fuel; solar thermal could provide around one-quarter; and geothermal and other renewable sources the remainder.

Energy efficiency is critical in the building sector. However, the slow rate at which energy efficiency in the sector is improving, due in part to the low building renovation rates of just 1% per year of existing building stock, remains a major issue. A three-fold increase in this renovation rate is necessary. In industry, the high energy demand of certain industries, the high carbon content of certain products, and high emission processes, require novel solutions and lifecycle thinking.

Figure ES2. Significant improvements in energy intensity are needed and the share of renewable energy must rise to two-thirds

Energy intensity improvement rate (%/yr) and renewable energy share in TFEC (%), Reference and REmap cases, 2015-2050

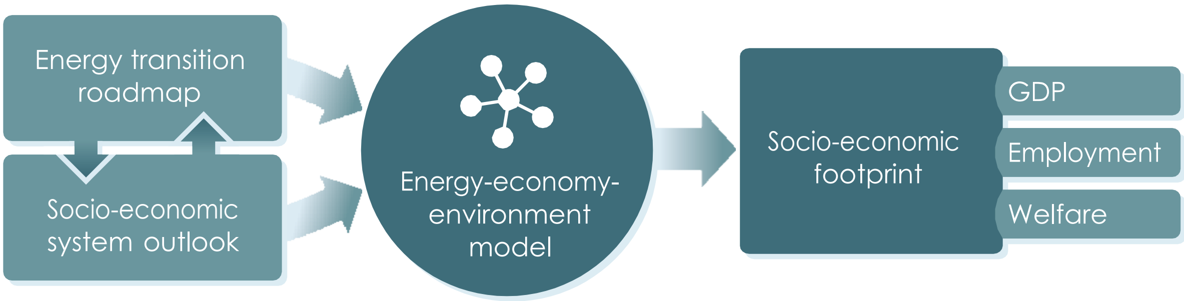


The global energy transformation makes economic sense. The additional costs of the comprehensive, long-term energy transition would amount to USD (United States Dollars) 1.7 trillion annually in 2050. However, cost-savings from reduced air pollution, better health and lower environmental damage would far outweigh these costs. The REmap Case suggests that savings in these three areas alone would average USD 6 trillion annually by 2050. In addition, the energy transition would significantly improve the energy system's global socio-economic footprint compared with business-as-usual, improving global welfare, GDP (Gross Domestic Product) and employment. Across the world economy, GDP increases by 2050 in both the reference and transition scenarios. The energy transition stimulates economic activity additional to the growth that could be expected under a business as usual approach. The cumulative gain through increased GDP from 2018 until 2050 would amount to USD 52 trillion

Substantial additional investment in low-carbon technologies will be required compared to current and planned policies. Cumulative investment in the energy system between 2015 and 2050 will need to increase around 30%, from USD 93 trillion according to current and planned policies, to USD 120 trillion to enable the energy transition. Investment in renewable energy and energy efficiency would absorb the bulk of total energy investments. Also included in this total is USD 18 trillion that would need to be invested in power grids and energy flexibility – a doubling over current and planned policies. In total, throughout the period, the global economy would need to invest around 2% of the average global GDP per year in decarbonisation solutions, including renewable energy, energy efficiency, and other enabling technologies.

Understanding the socioeconomic footprint of the energy transition is essential to optimise the outcome. The energy transition cannot be considered in isolation, separate from the socio-economic system[1] in which it is deployed. Different transition pathways can be pursued, as well as different transitions of the socio-economic system. The REmap Case significantly improves the global socioeconomic footprint of the energy system (relative to the Reference Case). By 2050, it generates a 15% increase in welfare, 1% in GDP, and 0.1% in employment. The GDP improvement peaks after about a decade, while welfare continuously improves to 2050 and beyond. The socioeconomic benefits of the transition (welfare) go well beyond GDP improvements, and include marked social and environmental benefits. At the regional level, the outcome of the energy transition depends on regional ambition as well as regional socioeconomic structures. Despite fluctuations in GDP and employment, welfare will improve significantly in all regions.

Figure ES3. Obtaining the socio-economic footprint from a given combination of an energy transition roadmap and a socio-economic system structure and outlook.

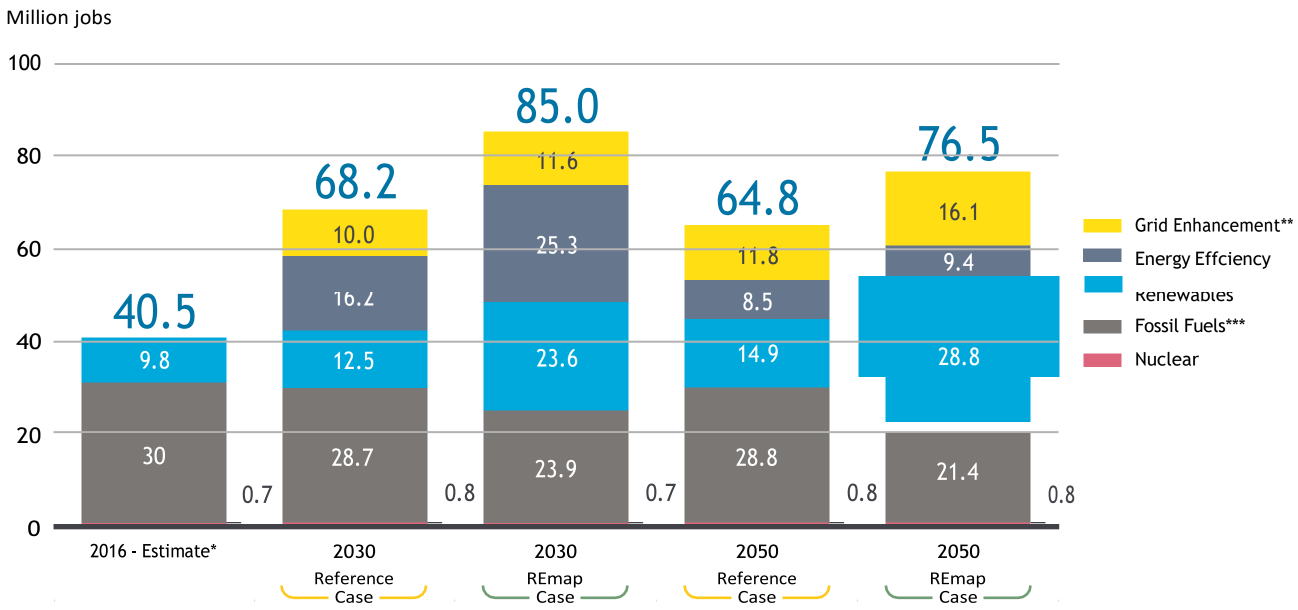


With holistic policies, the transition can greatly boost overall employment in the energy sector. On balance, the shift to renewables would create more jobs in the energy sector than arelost in the fossil fuel industry. The REmap Case would result in the loss of 7.4 million jobs in fossil fuels by 2050, but 19.0 million new jobs would be created in renewable energy, energy efficiency, and grid enhancement and energy flexibility, for a net gain of 11.6 million jobs. To meet the humanresource requirements of renewable energy and energy efficiency sectors in rapid expansion, education and training policies would need to meet the skill needs of these sectors and maximising local value creation. A transition that generates fair and just socioeconomic outcomes will avoidresistances that could otherwise derail or halt it. Transforming the socioeconomic system is one of the most important potential benefits.

1 This report often makes reference to the socio-economic conceptual construct. The socio-economic system includes all the social and economic structures and interactions existing within a society. The energy transitionis not to be deployed as a standalone component, but within the existing socio-economic system, with many and complex interactions taking place between them. Holistically addressing these interactions from the onset prevents barriers and opens the door to greater and deeper transformational potential. Improvements in both the energy transition and the socio-economic system, enhancing the synergies between them, contributes to boosting the overall transition outcome.

Figure ES4. The energy transition would generate over 11 million additional energy sector jobs by 2050

Employment in the overall energy sector, 2016, 2030 and 2050 (million jobs)



* Estimates for jobs in energy efficiency and grid enhancement are not available for 2016.

** The jobs in grid enhancement make reference to the jobs for T&D grids and Energy Flexibility, created in the development, operation and maintenance of infrastructure to enable the integration of RES into the grid.

*** Includes all jobs the fossil fuel industry including in their extraction, processing and consumption

All regions of the world stand to benefit from the energy transformation, although thedistribution of benefits varies according to socio-economic context. As expected, socio- economic benefits are not distributed uniformly across countries and regions. This is because the effects play out differently depending on each country's or region's dependence on fossil fuels, ambition in its energy transition, and socio-economic characteristics. In terms of welfare,the strongest overall improvements are found in Mexico, closely followed by Brazil, India and the countries and territories of Oceania. Other regions, including rest of East Asia, Southern Africa, Southern Europe, and Western Europe also record high welfare gains. Environmental benefits are similar in all countries, because they are dominated by reduced greenhouse gas (GHG) emissions given its global nature. Regional net gains in employment fluctuate over time, but the impact ispositive in almost all regions and countries.

Accelerated deployment must start now. Early action to channel investments in the right energy technologies is critical to reduce the scale of stranded assets. The slow progress of emission mitigation to date means that the adoption of a mitigation path detailed in this reportwill result in stranded assets worth more than USD 11 trillion. If the world starts to accelerate the energy transition today based largely on renewable energy and energy efficiency, it would limit the unnecessary accumulation of energy assets, which would otherwise have to be stranded; minimise the environmental and health damage caused by fossil fuel use; and reduce the need to resort in the future to environmentally questionable technologies, such as carbon capture and storage or nuclear power.

The financial system should be aligned with broader sustainability and energy transition requirements. Financial constraints and inertia can inhibit the investment required to deliver the energy transition. Increasing access to finance and lowering borrowing costs would increase both GDP and employment further, while also enabling the transition pathway detailed in this report. Policy measures and structural socioeconomic modifications increase the availability of finance without compromising regional financial stability. Sources of finance that currently contribute little to sustainable energy investment should be unlocked. Potential sources include institutional investors (pension funds, insurance companies, endowments, sovereign wealth funds) and community-based finance. Scarce public finances should be used to mitigate key risks and lower the cost of capital in countries and regions where renewable energy investments are perceived to be high risk. Rapid action is required to remove this potentially significant transition barrier and ensure that the introduction of clean and modern energy sources is not further delayed.

Focus areas

While the energy transition described in this report is technically feasible and economically beneficial, it will not happen by itself. Policy action is urgently needed to steer the global energy system towards a sustainable pathway.

This report identifies six focus areas where policy and decision makers need to act:

1. **Tap into the strong synergies between energy efficiency and renewable energy.** Thisshould be among the top priorities of energy policy design because their combined effect can deliver the bulk of energy-related decarbonisation needs by 2050 in a cost-effective manner.

2. **Plan a power sector for which renewables provide a high share of the energy.** Transforming the global energy system will require a fundamental shift in the way energy systems are conceived and operated. This, in turn, requires long-term energy system planning and a shift to more holistic policy-making and more co-ordinated approaches across sectors and countries. This is critical in the power sector, where timely infrastructure deployment and the redesign of sector regulations are essential conditions for cost-effective integration of solar and wind generation on a large scale. These energy sources will become the backbone of power systems by 2050.

3. **Increase use of electricity in transport, building and industry**. Urban planning, building regulations, and other plans and policies must be integrated, particularly to enable deep and cost-effective decarbonisation of the transport and heat sectors through electrification. However, renewable electricity is only part of the solution for these sectors. Where energy services in transport, industry and buildings cannot be electrified, other renewable solutions will need to be deployed, including modern bioenergy, solar thermal, and geothermal. To accelerate deployment of these solutions, an enabling policy framework will be essential.

4. Foster system-wide innovation. Just as the development of new technologies has played a key role in the progress of renewable energy in the past, continued technological innovation will be needed in the future to achieve a successful global energy transition. Efforts to innovate must cover a technology's full life-cycle, including demonstration, deployment and commercialisation. But innovation is much broader than technology research and development (R&D). It should include new approaches to operating energy systems and markets as well as new business models. Delivering the innovations needed for the energy transition will require increased, intensive, focused and co-ordinated action by national governments, international actors and the private sector.

5. Align socio-economic structures and investment with the transition. An integrated and holistic approach is needed by aligning the socio-economic system with the transition requirements. Implementing the energy transition requires significant investments, which adds to the investment required for adaptation to climate change already set to occur. The shorter the time to materialize the energy transition, the lower the climate change adaptation costs and the smaller the socio-economic disruption. The financial system should be aligned with broader sustainability and energy transition requirements. Investment decisions made today define the energy system of decades to come. Capital investment flows should be reallocated urgently to low-carbon solutions, to avoid locking economies into a carbon-intensive energy system and to minimise stranded assets. Regulatory and policy frameworks must be established quickly which give all relevant stakeholders a clear and firm long-term guarantee that energy systems will be transformed to meet climate goals, providing economic incentives that fully reflect the environmental and social costs of fossil fuels and removing barriers to accelerate deployment of low carbon solutions. The increased participation of institutional investors and community-based finance in the transition should be facilitated and incentivized. The specificities of distributed investment needs (energy efficiency and distributed generation) should be addressed.

6. Ensure that transition costs and benefits are fairly distributed. The scope of the transition required is such that it can only be achieved by a collaborative process that involves the whole of society. To generate effective participation, the costs and benefits of the energy transition should be shared fairly, and the transition itself should be implemented justly. Universal energy access is a key component of a fair and just transition. Beyond energy access, huge disparities exist at present in the energy services available in different regions. The transition process will only be complete when energy services converge in all regions. Transition scenarios and planning should incorporate access and convergence considerations. A social accounting framework that enables and visualizes the transition contributions and obligations from individuals, communities, countries and regions should be promoted and facilitated. Advances should be made in the definition and implementation of a fair context to share the transition costs, while promoting and facilitating structures that allow a fair distribution of the transition benefits. Just transition considerations should be explicitly addressed from the onset, both at the micro and macro levels, creating the structures that provide alternatives allowing those individuals and regions that have been trapped into the fossil fuel dynamics to participate from the transition benefits.

INTRODUCTION

The global energy system has to be transformed. An energy supply system based largely on fossil fuels has to be based, instead, on renewable energy. This report sets out a path to energy system decarbonisation based on high energy efficiency and renewable energy. It provides evidence showing how the transition is occurring, and how the deployment of renewables is makingenergy supply more sustainable.

This report also demonstrates that decarbonisation is both technically feasible and can be achieved at a lower cost and with greater socio-economic benefits than business as usual.**This can create a world that is both more prosperous and exposed to fewer long-term risks.**

The starting objective of the analysis is to limit the global temperature rise to below 2°C in the present century, with 66% probability. Although energy-related CO_2 emission growth in 2014-2016 was flat, estimated emission levels increased by 1.4 % in 2017 to reach a historic high of 32.5 Gt (IEA, 2018a). Currently, the world is not nearly on course to meet the well below 2°C climate objective, and even further from attaining the aspirational target of limiting warming to 1.5°C.

Nevertheless, the power sector registered significant progress in some areas during 2017. **The deployment of renewables reached record levels, in terms of both power generation and capacity addition** (IRENA, 2018a). Record increases were also recorded in electromobility and other forms of electrification of end uses (such as heat pumps), while the use of modern bioenergy and solar thermal and geothermal energy also increased. **Overall the share of renewables in total final energy consumption grew by an estimated 0.25%, to around 19% of TFEC, a new record.**

Growth in renewable energy must nevertheless greatly accelerate. The world needs to increase the share of renewable energy in TFEC from 19% in 2017 to two-thirds by 2050. In parallel, theglobal economy needs to reduce energy intensity by 2.8% per year on average to 2050, compared with the 1.8% annual fall achieved in recent years. This would bring global energy consumption in 2050 to slightly below current levels despite significant population and economic growth over the period. Improvements in energy efficiency slowed in the last few years, causing carbon dioxideemissions to rise in 2017. A recent report by the International Energy Agency (IEA) nevertheless indicates progress and suggests that abundant opportunities exist to accelerate energy efficiency worldwide (IEA, 2018b).

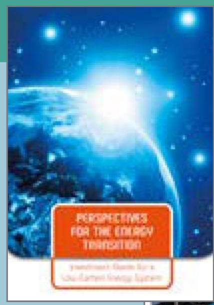
This report sets out how an energy transition acceleration could be achieved. It outlines the supply side and demand side technological changes required, and indicates the level of investment needed. It also analyses the costs and benefits of energy transition. It concludes that the additionalcost of energy transition (about USD 1.7 trillion annually in 2050) are dwarfed by the benefits (on average USD 6.3 trillion in the same year). If a more broad-based welfare indicator is considered, overall benefits could be much higher. Global GDP would also grows and would be 1% larger in2050 compared to the Reference Case, which is based on current and planned policies including Nationally Determined Contributions (NDCs). Millions of additional jobs would be created worldwide. **In sum, a sustainable energy future is technically and economically feasible.**

The global energy system must be transformed. Although addressing climate change remains a key driver, the energy transition brings a much wider range of benefits than simply carbon emissions reduction. It can make universal energy access affordable, improve human health, increase energy security and diversify energy supply. A new International Renewable Energy Agency's (IRENA) Commission on the geopolitics of energy transition is currently mapping suchimpacts (IRENA, 2018b). At the same time, the energy sector alone will not provide every solution. A holistic approach to energy transition should be adopted that considers all facets of the economy and society. The transition should also be just: policies should promote universal energy access andidentify and support those who will be adversely affected by changes the transition would bring.

While many approaches can reduce energy-related carbon emissions – a key driver of climate change - there is universal agreement that energy efficiency and renewable energy are the two main pillars. The report describes and provides guidance on how to manage the transition. Energy systems can of course be transformed in many different ways: the report describes one,based on IRENA's understanding of current technology.

The majority of the technologies presented in the report are available today, and theirdeployment can be accelerated immediately. This said, new technological solutions need to be found and applied in some areas. A number of emerging technologies need to be pioneered andsupported. They include examples such as offshore wind, innovative storage solutions, electricmobility, renewable hydrogen, and advanced biofuels for aviation. If the world starts working towards the energy transition today, it could achieve substantial emission reductions, includingthose necessary to keep the rise in average global temperate below 2°C; limit the accumulation of energy assets that would become obsolete before the end of their technical lifetime, costing many trillions of dollars; minimise collateral damage caused by fossil fuel use; and reduce the need tohave recourse in the future to environmentally questionable technologies such as carbon capture and storage (CCS) in the power sector.

Box 1 This report and its focus



In March 2017, IRENA and the IEA issued a report, *Perspectives forthe Energy Transition: Investment needs for a low-carbon energy system* (IEA and IRENA, 2017). Several subsequent reports set out IRENA's analysis in more detail. They included: *Accelerating the Energy Transition through Innovation* (IRENA, 2017a), *Stranded Assets and Renewables* (IRENA, 2017b), and *Synergies between Renewable Energy and Energy Efficiency* (IRENA, 2017c). Also in recent years IRENA has released numerous reports examining the socio-economic benefits of renewable energy, including *Renewable Energy Benefits - Measuring the Economics* and a series of reports focused on renewable energy benefits, on leveraging local industries and capacities and an annual review of employment in the renewable energy industry (IRENA, 2017d; 2017e; 2016).

Global policy frameworks and energy markets continue to evolve, and the situation has changed since these analyses were released. Important market developments are also taking place. Because the cost of renewable energy technologies continues to fall, projections of renewable energy in country energy plans have risen. The increasing attractiveness of renewable energy technologies also influences investment flows. This report therefore updates IRENA's REmap analysis of key countries and regions.

Based on the updated REmap transition pathway presented in this report, new socio-economic analysis has also been conducted, and this report presents new findings on how the transition would affect socio-economic footprints and key indicators such as GDP, employment and welfare. It also touches on how to finance the transition.

The scope, complexity and detail of country discussions have evolved significantly. Where discussions once focused primarily on renewable energy deployment, they now consider how high shares of variable renewable energy (VRE) can be incorporated in power grids, the role of electrification, solutions for decarbonising heating and transport demand, and more integrated long-term planning of energy systems. This illustrates how dynamic and broad the challenges are and the opportunities that the energy transition raises. Recognising this, the report proposes not just an energy pathway for the energy transition, but focus areas to help policy makers understand and plan for the energy transition.

The results indicate why we need an energy transition, what it might look like, who will be affected, and, last but not least, how much it will cost. To better examine these implications, this report focuses its analysis on two possible pathways for the global energy system:

Reference Case. This scenario takes into account the current and planned policies of countries. It includes commitments made in NDCs and other planned targets. It presents a "business-as-usual" perspective, based on governments' current projections and energy plans.

REmap Case. This analyses the deployment of low-carbon technologies, largely based on renewable energy and energy efficiency, to generate a transformation of the global energy system which for the purpose of this report has the goal of limiting the rise in global temperature to below 2°C above pre-industrial levels by the end of the century (with a 66% probability).

For more information about the REmap approach and methodology, please visit:
http://www.irena.org/remap/methodology

STATUS OF THE ENERGY TRANSITION: **A MIXED PICTURE**

The energy transition is underpinned by the rapid decline of renewable energy costs. Additions to renewable power capacity are exceeding 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 PV and 47 GW by wind power (including 4 GW of offshore wind) (IRENA, 2018a). Renewable power generation accounted for an estimated quarter of total global power generation in 2017, a record.

At the same time, costs, including the costs of solar PV and wind, continue to fall. Lower costs open the prospect of electricity supplies dominated by renewables, but also herald a shift to clean renewable energy for all kinds of uses. The decline in costs of some new emerging technologies are also surprising. In 2017, offshore wind projects were offered at market prices without requiring subsidy for the first time, and concentrated solar power including thermal storage was being offered at less than 10 US cents per kilowatt-hour (kWh) (IRENA, 2018c).

Auction results and continued technical innovations suggest that costs will fall further in the future. Solar PV costs are expected to halve again by 2020 (relative to 2015-2016). Between early 2017 and early 2018, global weighted average costs for onshore wind and solar PV stood at USD 6 cents and USD 10 cents per kWh, respectively (IRENA, 2018c). Recent auction results suggest that some future projects will significantly undercut these averages.

The integration of renewable power in power systems also broke records in 2017. Remarkably, solar and wind power provided over half of the power produced in the eastern region of Germany. In that region, the utility 50Hertz has demonstrated the economic and technical feasibility of running power systems reliably with a high share of variable renewables (50Hertz,n.d.). Many jurisdictions around the world deployed higher levels of renewable power than theyever had before, for days, weeks or months. There is ample evidence by now that power systems dominated by renewables can work and be an important asset, underpinning economic growth.

These recent trends show clearly that growth in renewable power is accelerating. At the same time, current growth rates are insufficient to achieve the level of decarbonisation required by 2050. Significant additional electrification of heating, transport and other energy services will be required, and growth in renewable power must continue to accelerate to make this possible.

Outside the power sector, progress is lagging. Electricity accounts for 20% of the total final energy consumption for transport, heat and other energy services (broadly defined as the end-use sectors of building, industry and transport). Around 80% is obtained from other sources, notably fossil fuels and direct use of renewable thermal energy or fuels. In the end-use sectors, energyefficiency is critical, but renewable sources such as solar thermal and geothermal energy, and bioenergy, can play an important role. Furthermore, increasing the share of electricity, and theshare of renewables in electricity supply, will raise the share of renewables in end-use sectors.

Electrification opens up the prospect of decarbonised road transport. In 2017, an estimated 1.2 million new electric vehicles were sold globally (around 1.5% of all car sales), a record level(Spiegel, 2018). China passed the United States to become the largest market. Sales of electric vehicles have grown rapidly in the last five years at a compound annual growth rate of 52%. **Over one billion electric vehicles could be on the road by 2050 if the world starts soon on the path to decarbonisation detailed in this report.**

The building sector consumes proportionately more electricity than other end-use sectors. Fossil fuels are mainly used for heating and cooking. Electrification for cooking and modern cookstoves are important alternatives for hundreds of millions of people who cook using traditional biomass. In terms of heating, heat-pump deployment achieved a new record in 2017. Building codes are aiming for near-zero or even energy positive buildings in the near future, for example in Japan. However, the slow rate at which the energy efficiency in the sector is improving, due in part tothe low building renovation rates of just 1% per year of the existing stock, remains a major issue. Athree-fold increase in the renovation rate is necessary.

The most challenging sector is industry. The high energy demands of certain energy intensive industries, the high carbon content of certain products, and the high emissions of certain processes make innovative solutions and lifecycle thinking necessary. Heavy industry as a whole has advanced far in increasing its use of renewables in 2017 or in the immediately preceding years; but electrification and the development of innovative technological solutions for biochemical and renewable hydrogen feedstock (for example, for primary steel making) continue apace.

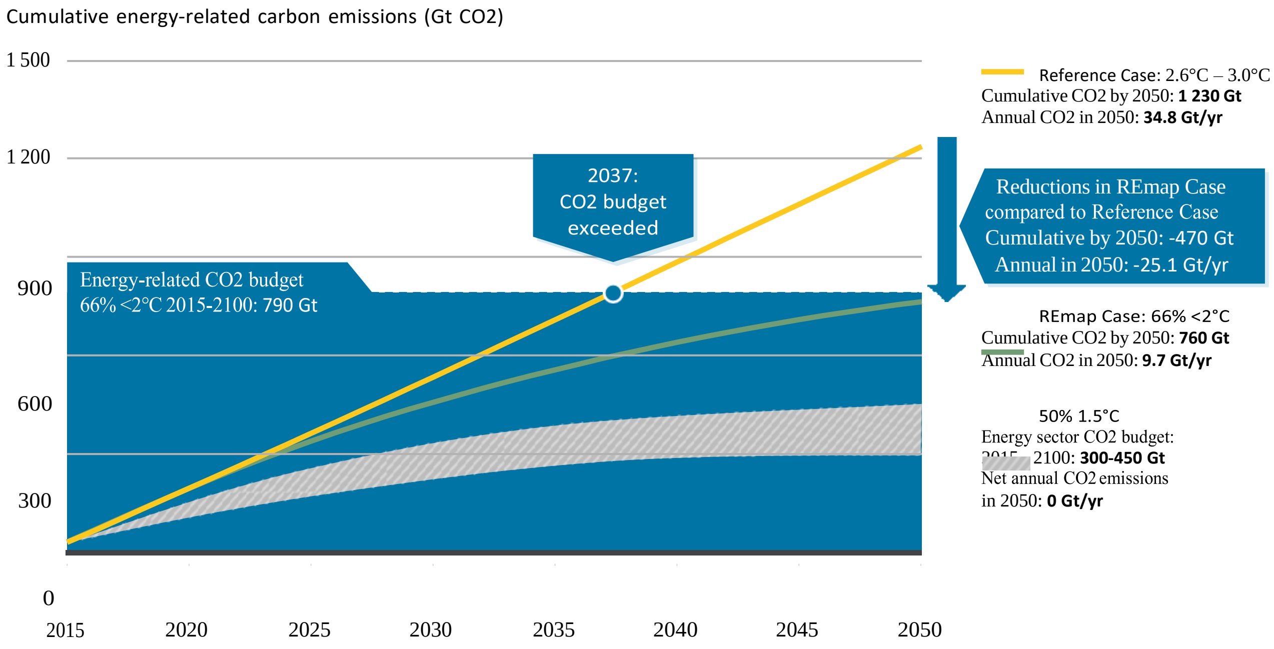
ENERGY-RELATED CARBON DIOXIDE EMISSIONS: **BRIDGING THE GAP**

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 year. The Reference Case indicates the projected fall in cumulative energy-related CO_2 emissions as a result of these revised policies and plans, including NDCs. Projected energy-related CO_2 emission in the Reference Case between 2015 and 2050 have declined from 1 380 Gt to 1 230 Gt, an 11% drop compared to the previous year analysis. However, this improvement is not yet reflected in current CO_2 emissions which grew by around 1.4% in 2017 (IEA, 2018a).

Government plans also still fall short of emission reduction needs. The Reference Case indicates that, under current and planned policies, the world will exhaust its energy-related CO_2 emission budget in under 20 years. To limit the global temperature increase to below 2°C (with a 66% probability), cumulative emissions must be reduced by a further 470 Gt by 2050 (compared to current and planned policies as shown in Figure 1).

Figure 1. In under 20 years, the global energy-related CO_2 emissions budget to keep warming below 2°C would be exhausted

Cumulative energy-related CO_2 emissions and emissions gap, 2015-2050 (Gt CO_2)



Based on current policies (set out in the Reference Case), in under 20 years, cumulative energy-related emissions will exceed the carbon budget required to hold temperature increases below 2°C. Emission reductions of 470 Gt will be needed by 2050 to reduce warming to 2°C.

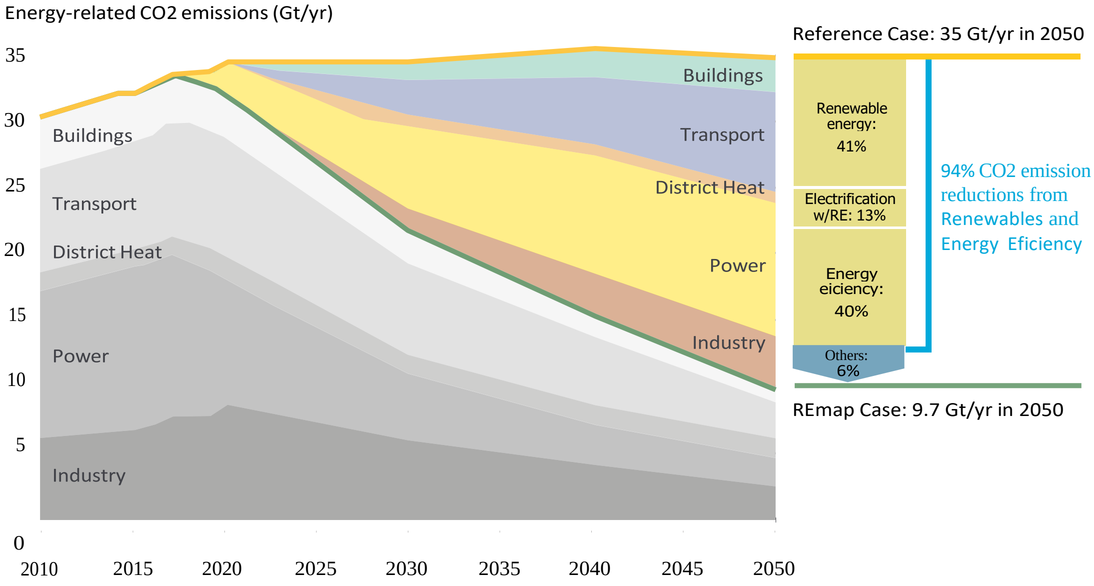
According to the Reference Case (which reflects current and planned policies including NDCs), energy-related CO_2 emissions will increase slightly year on year to 2040, before dipping slightly by 2050 to remain roughly at today's level (Figure 2). This is an improvement relative to the 2017 analysis, which found annual CO_2 emissions were higher in 2050, and shows that NDCs andthe rapidly improving cost and performance of renewable energies are having an effect on long-term energy planning and scenarios (IRENA, 2017f). However, significant additional reductions are needed. To meet a climate target of limiting warming 2°C, annual energy-related CO_2 emissions still need to decline by 2050 from 35 Gt (in the Reference Case) to 9.7 Gt, a fall of more than 70%.

IRENA's analysis concludes that renewable energy and energy efficiency, coupled with deep electrification of end-uses, can provide over 90% of the reduction in energy-related CO_2 emissions that is required. The remainder would be achieved by fossil fuel switching (to natural gas) and carbon capture and sequestration in industry for some of industrial process emissions.Nuclear power generation would remain at 2016 levels. Simultaneously, a significant effort is required to reduce carbon emissions generated by industrial processes and land use to less thanzero by 2050. The climate goal cannot be reached without progress also in those areas.

Additionally, if the climate objective was raised to restrict global temperature rise to 1.5° C, the aspirational goal of the Paris Agreement, this would require significant additional emission reductions and a steeper decline in the global emission curve. Energy-related CO_2 emissions of about zero would be necessary by around 2040 if emissions did not become net-negative at any point, or would need to fall to zero by 2050 if negative emission technologies were employed in the second half of the century.

Figure 2. Renewable energy and energy efficiency can provide over 90% of the reduction in energy-related CO_2 emissions

Annual energy-related CO_2 emissions and reductions, 2015-2050 (Gt/yr)



Annual energy-related emissions are expected to remain flat (under current policies in the Reference Case) but must be reduced by over 70% to bring temperature rise to below the 2°C goal. Renewable energy and energy efficiency measures provide over 90% of the reduction required.

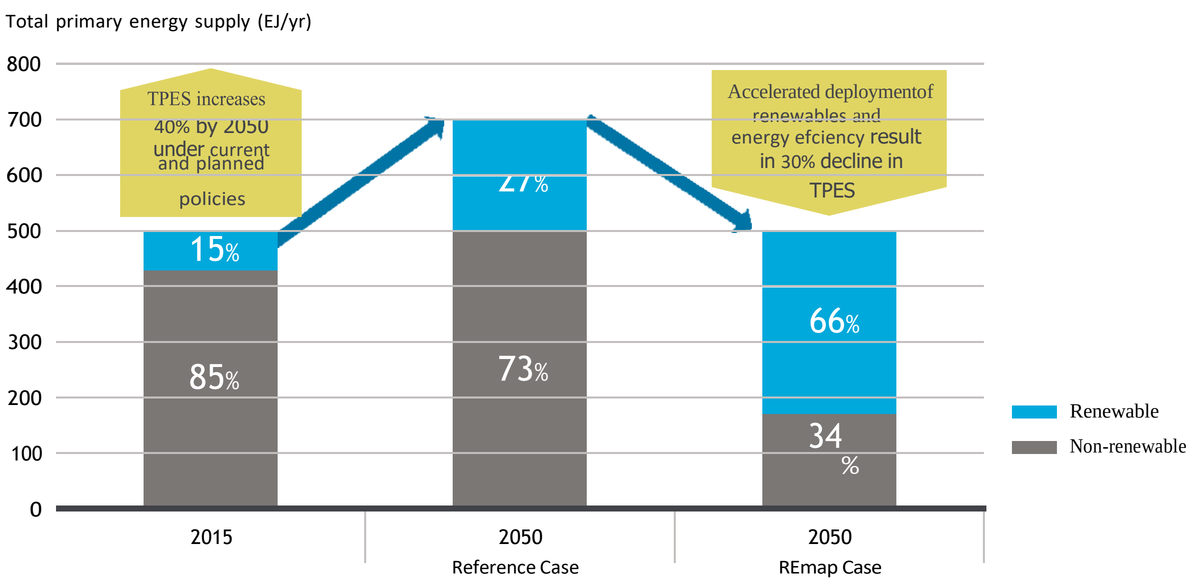
A PATHWAY FOR THE TRANSFORMATION OF THE GLOBAL ENERGY SYSTEM

The total share of renewable energy must rise from around 15% of TPES in 2015 to around 66% in 2050 (Figure 3). Under current and planned policies, the Reference Case suggests, this share increases only to 27%. Under the REmap Case, renewable energy use would nearly quadruple from 64 exajoule (EJ) in 2015 to 222 EJ in 2050. The renewable energy mix would change, from one dominated by bioenergy to one in which over half of renewable energy would be solar andwind-based. Bioenergy would continue to account for about one-third of renewable consumption by 2050.

Remarkably, because it leverages the vast synergies between renewable energy and energy efficiency, under the REmap Case TPES would fall slightly below 2015 levels, despite significant population and economic growth. To make the substantial energy efficiency improvements required, the global economy needs to reduce energy intensity by 2.8% per year on average to2050, compared with the 1.8% annual fall achieved in recent years.

Figure 3. The global share of renewable energy would need to increase to two-thirds and TPES would need to remain flat over the period to 2050

TPES and the share of renewable and non-renewable energy under the Reference and REmap cases, 2015-2050 (EJ/yr)



Under current and planned policies (the Reference Case) TPES is expected to increase almost 40% by 2050. To achieve a pathway to energy transition (the REmap Case), energy efficiency would need to reduce TPES slightly below 2015 levels, and renewable energy would need to provide two-thirds of the energy supply.

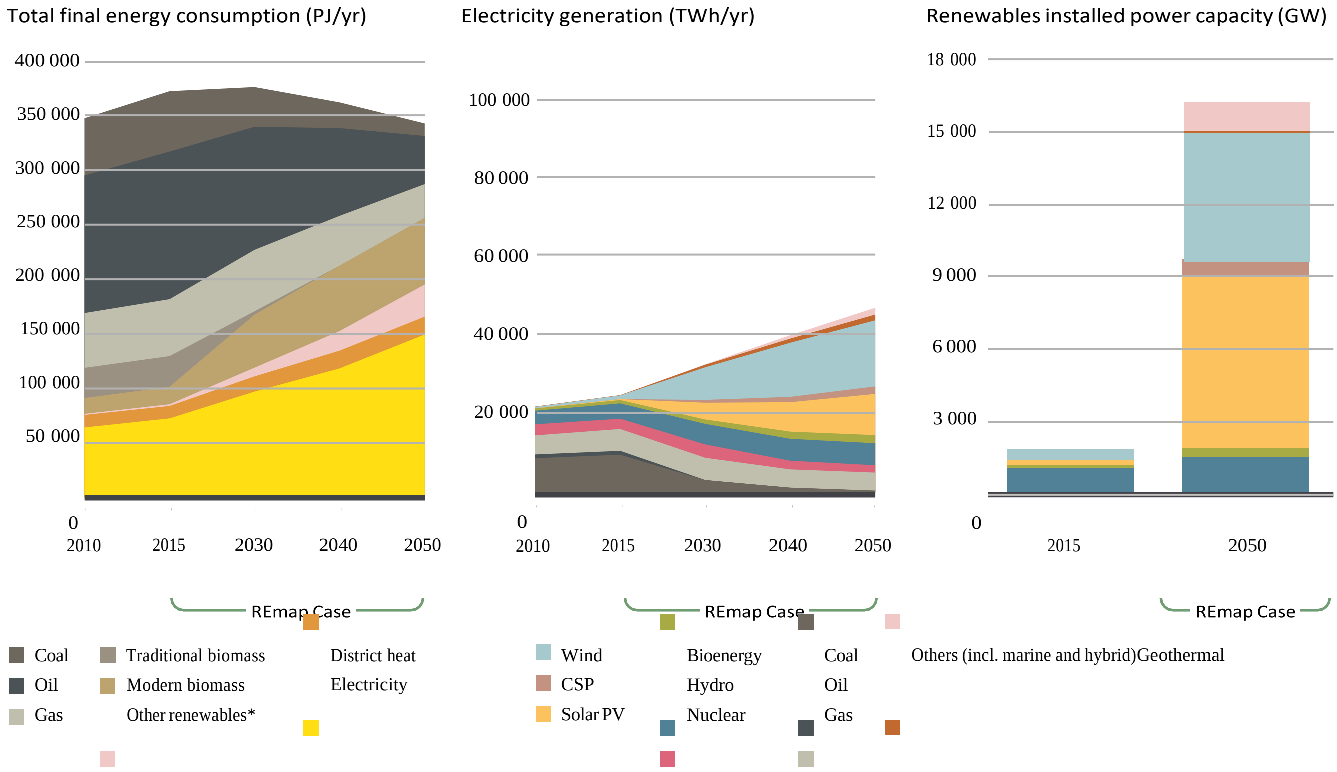
Notes: Data include energy supply in electricity generation, district heating/cooling, industry, buildings and transport sect ors. These sectors accounted for 85% of global total

The acceleration envisaged in the REmap Case would significantly transform the global energy system. The power sector would be underpinned by the wide-scale deployment of renewable energy and increasingly flexible power systems, supporting cost-effective integration. The share of renewable energy in the power sector would increase from 25% in 2017 to 85% in 2050. This transformation would require new approaches to power system planning, system and market operations, and regulation and public policy. Renewable electricity would account for just under 60% of total renewable energy use in final energy terms, two and a half times today's share.

As low-carbon electricity becomes the preferred energy carrier, the share of electricity consumed in end-use sectors would need to increase from approximately 20% in 2015 to 40%in 2050 (Figure 4). For example, electric vehicles and heat pumps would become much more common in most parts of the world. While renewable power would account for just under 60% of renewable energy consumption, direct use of renewable energy would be responsible for a sizeableproportion of energy use in industry, buildings and transport. Two-thirds of this would involve direct use of biomass; around one-quarter would be generated by solar thermal and the remainder by geothermal and other renewable sources.

Figure 4. The rising importance of electricity derived from renewable energy

Share of electricity in total final energy consumption (PJ/yr), electricity generation mix (TWh/yr), and renewable capacity developments (GW), REmap Case, 2015-2050



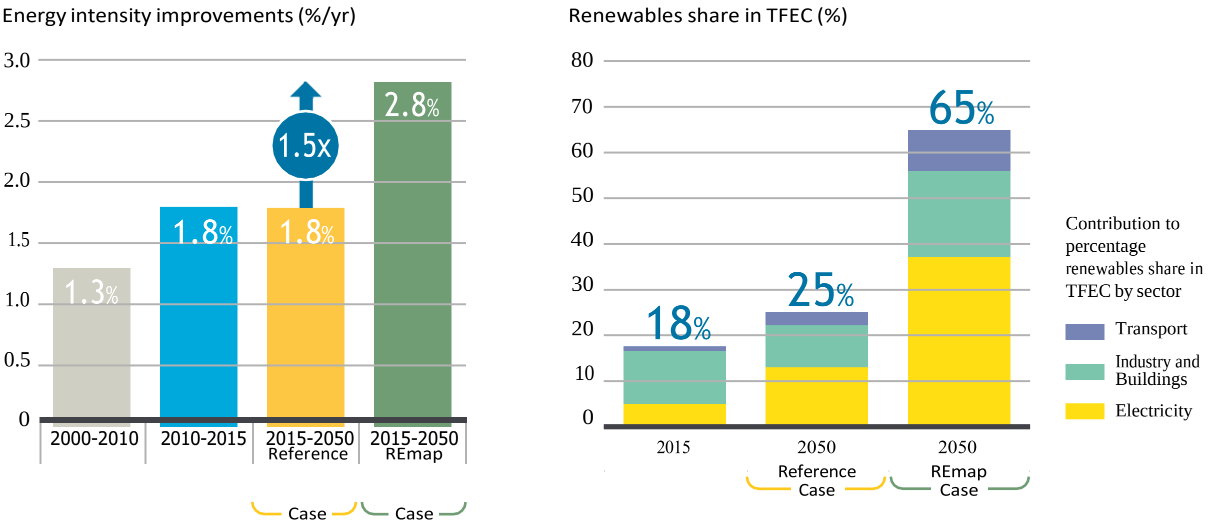
*includes solar thermal, geothermal heat and hydrogen

The share of electricity in total final energy consumption needs to double between 2015 and 2050.

The energy intensity of the global economy would need to fall by about two-thirds by 2050. In recent years, energy intensity has been falling at around 1.8% per year (Figure 5). The rate of fall would need to increase one-and-a-half times, to 2.8% per year. The share of renewable energy in TFEC would have to increase from 18% in 2015 to 65% in 2050. In recent years, the annual increase in the percentage share of renewable energy has been around 0.2 percentage point per year, and estimates suggest it increased by 0.25 percentage points in 2017. A six to seven-fold increase is therefore needed (from 0.2-0.25 percentage point per year to 1.4 percentage point per year) to raise the share from 18% to 19.4% in the first year and then incrementally, to reach 65% in 2050.

Figure 5. Significant improvements in energy intensity are needed and the share of renewable energy must rise

Energy intensity improvement rate (%/yr) and renewable energy share in TFEC (%), Reference and REmap cases, 2015-2050



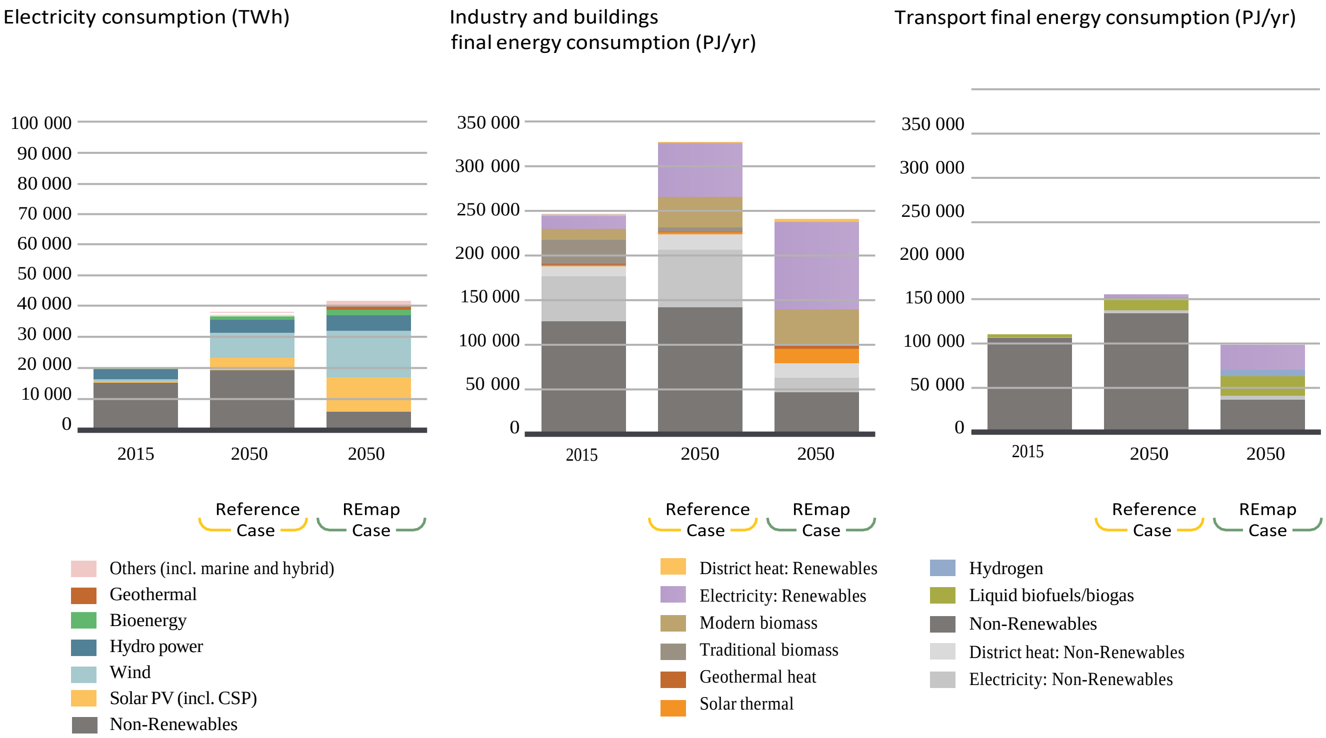
Source: Historical energy intensity improvement values from (SE4ALL, 2016), projections based on IRENA analysis

Both renewable energy and energy efficiency are at the heart of the energy transition and climate goals. By 2050 action in both areas must be scaled up considerably.

Modern bioenergy can play a vital role in the energy transition if scaled up significantly. Although more modern bioenergy has been used in recent years, its growth 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 bioenergycould provide key solutions. Bioenergy will have to be sourced from sustainable and affordablefeedstocks.

Figure 6. Renewable energy should be scaled up to meet power, heat and transport needs

Use of renewable and fossil energy in electricity generation, buildings and industry, and transport - Reference and REmap cases, 2015-2050 (TWh/yr or PJ/yr)



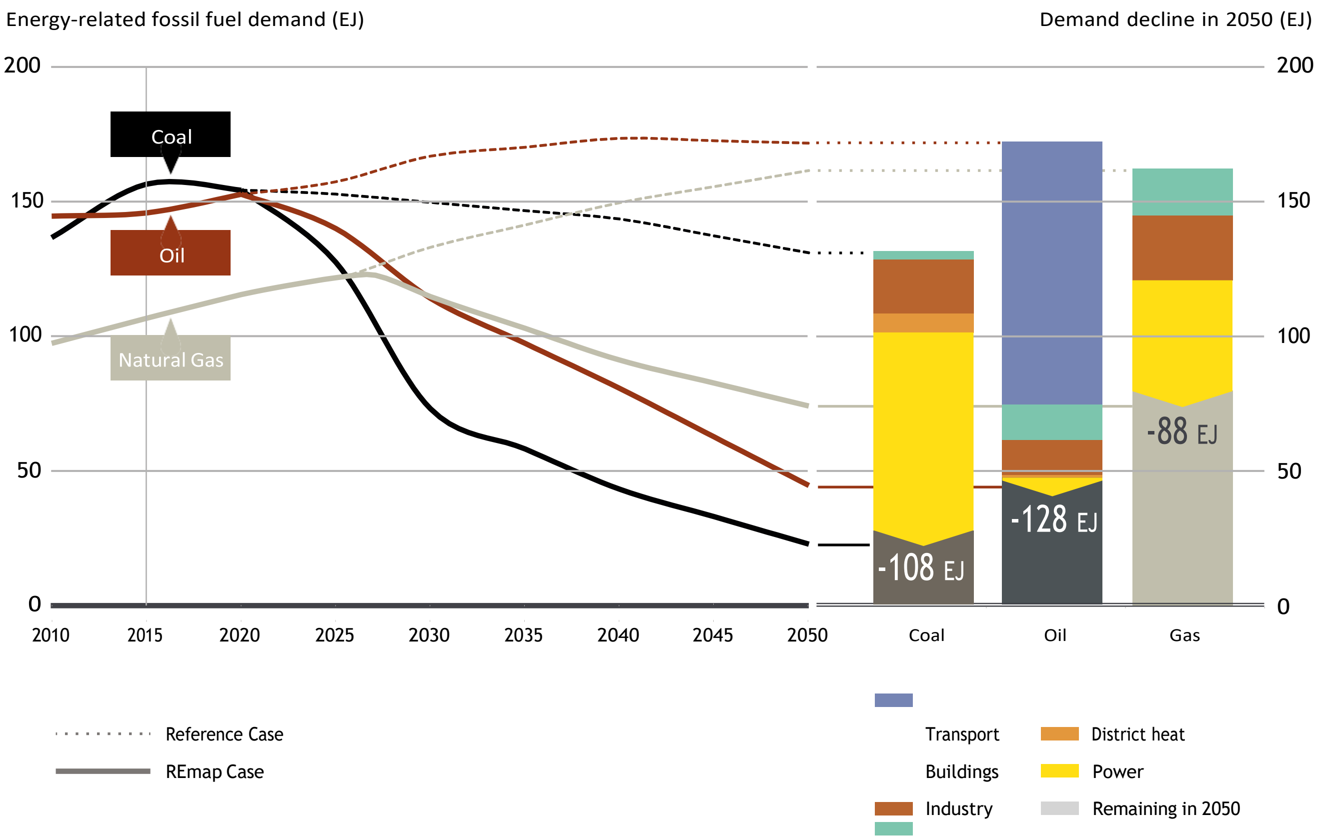
Note. Since 3.6 PJ equals 1 TWh, the axis for electricity consumption on the left is scaled to match the values of the other two figures, making comparison possible.

The share of electricity rises to 40% of TFEC in the REmap Case, and 85% of electricity generation is from renewable sources.

By 2050 in the REmap Case, fossil fuel use for energy would fall to one-third of today's levels. Oil and coal would decline most, 70% and 85% respectively. Natural gas use would peakaround 2027, and would be the largest source of fossil fuel by 2050, however with production declining 30% from the present level.

Figure 7. The declining importance of fossil fuels

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



Note: Figure includes only fossil fuel use for energy and excludes non-energy use.

Under the REmap Case, both oil and coal demand decline significantly and continuously, and natural gas demand peaks around 2027. In 2050, natural gas is the largest source of fossil fuel.

COUNTRY AMBITION FOR THE ENERGY TRANSITION

The renewable energy mix will change considerably over the coming decades. The mix today includes significant use of traditional bioenergy; in the future, the mix will increasingly be dominated by renewable electricity, advanced biofuels, and electrification technologies (largely utilising renewable power), including electric vehicles and heat-pumps. The largest renewable energy markets approximately match the areas of greatest energy demand (China, the USA, India and the EU) but Brazil, Indonesia, Japan and Canada are also important markets. The Group of Twenty (G20) countries made up 60% of global renewable energy consumption in 2015 but will be responsible for almost 85% in 2050 in the REmap Case.

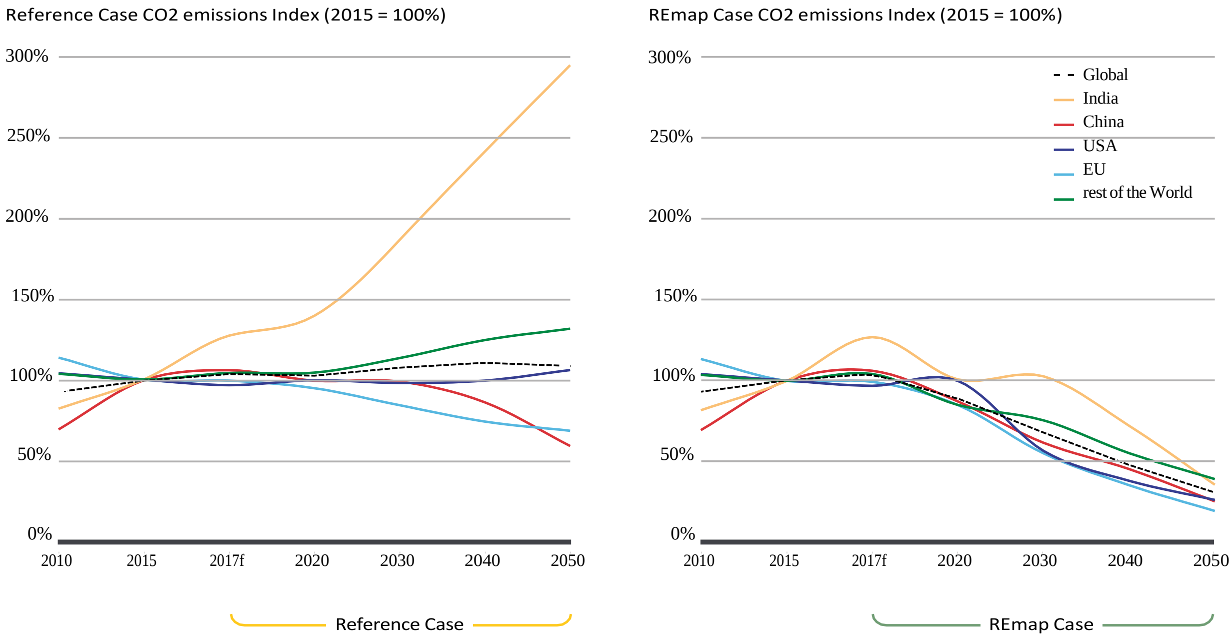
In 2015, the share of renewables in country energy systems ranged from just above zero to over 50%. According to current and planned policies (the Reference Case), most countries foresee modest increases in renewable energy while some even forecast a decline in the share of renewable energy by 2050. In India and Indonesia, this is explained by falls in traditional bioenergy use following the adoption of more efficient cooking stoves that use bioenergy or other fuels such as liquefied petroleum gas or kerosene. China is an interesting case: the share of renewables growsby far more than in any other G20 country (both in percentage and absolute terms); most of thisgrowth occurs between 2030 and 2050.

The report's analysis shows that all countries can substantially increase renewable energy as a proportion of total energy by 2050. The REmap Case shows that every country has a different potential to add renewable energy but the potential is substantial in all cases. In countries such as Canada, India and the United States of America, projections raise the share of renewables in total final energy use to above 60%. With a few exceptions, such as the Russian Federation and Saudi Arabia, the share of renewables in all countries exceeds 40%, and many exceed 60%. The highest shares are projected in countries such as Brazil, France and Germany. When the increase in renewable share is combined with higher energy efficiency, the effect is a significant drop in energy-related CO_2 emissions (Figure 8).

Along with renewable energy, energy efficiency is a key driver of reduced energy-related CO_2 emissions in the energy transition. At country level, the energy intensity of GDP would fall by between 50% and 75%. Such a fall is required across all energy consuming economies. The largest declines are required in India and China, where falls in energy intensity would bring energy intensity levels to just 20% or 25% of 2015 levels by 2050. Energy intensity levels in the EU and USA must also drop steeply to about half today's levels.

Figure 8. A rapid and significant decline in energy-related CO_2 emissions is necessary in all countries

Energy-related CO_2 projections in selected countries - Reference and REmap Cases, 2010-2050 (% change compared to 2015)



Source: Historic emission values from (IEA, 2015), projections based on IRENA analysis

Under the REmap Case, emissions in countries fall to between 20% and 40% of 2015 levels by 2050.

Action at country level is key to driving the energy transition forward. Many countries are advancing towards the energy transition, but despite positive steps, no country is yet on a pathwaythat will achieve the energy transition's goals:

- **China** is the world's largest energy producer, consumer, and power generator. At the same time, it ranks top in terms of installed hydropower, and wind and solar PV power generation capacity, and is the largest user of solar water heaters and geothermal heat. In 2015, renewables provided 7% of China's total final energy use. Under the REmap Case, this share increases to 67% by 2050.
- **The European Union** has been at the forefront of global renewable energy deployment and has played a key role in raising international awareness and advancing policy action to address the global challenge of climate change. The region has nearly doubled its share of renewable energy from 2005 to 2015 to reach almost 17%. However, more effort will be needed to meet long-term decarbonisation commitments and the region would need to increase this share to 70% by 2050.
- **India** is advancing towards its target to achieve 175 GW of renewable power capacity by 2022. In 2015, renewables accounted for 36% of India's final energy use, one of the highest shares in the G20 countries. However, if traditional use of bioenergy is excluded, its share of modern renewables is around 10%. Under the REmap Case, India would increase the share of modern renewables to 73% by 2050.
- **The United States of America** continues to introduce renewables at a strong pace despite some headwinds. Renewables currently account for just 8% of total final energy use; the country needs to increase that share to 63% under the REmap Case.

Table 1. Key indicators relevant to the energy transition in selected countries (REmap Case)

	CHINA		EU		INDIA		USA	
	2015	2050	2015	2050	2015	2050	2015	2050
Share of renewable energy in primary energy supply	5%	69%	13%	74%	9%	75%	9%	63%
Share of renewable energy in final energy use	7%	67%	17%	70%	10%	73%	8%	63%
Electricity use in final energy consumption	19%	54%	22%	41%	18%	48%	20%	51%
Share of renewable energy in power	26%	94%	29%	94%	15%	92%	14%	78%
	Reference Case	REmap Case	Reference Case	REmap Case	Reference Case	REmap Case	Reference Case	REmap Case
Decarbonisation investments between 2015 and 2050* (USD trillion)	15	22.4	5.4	8.6	6.4	10.2	6	14.1
	2030	2050	2030	2050	2030	2050	2030	2050
GDP impact**		1.4%	N/A	N/A	0.9%	-0.4%	1.6%	1.8%
Employment impact**		0.3%	N/A	N/A	0.5%	0.2%	0.2%	0.4%

Note: Shares of renewable energy in final energy use refer to modern renewable energy

* Investments include investments in renewable energy (for power and end-uses), in energy efficiency and infrastructure, and in energy flexibility to integrate renewables in the power sector.

** The figures show the difference in GDP and employment between the REmap Case and the Reference Case.

ANALYSIS
AND INSIGHTS
IN KEY SECTORS

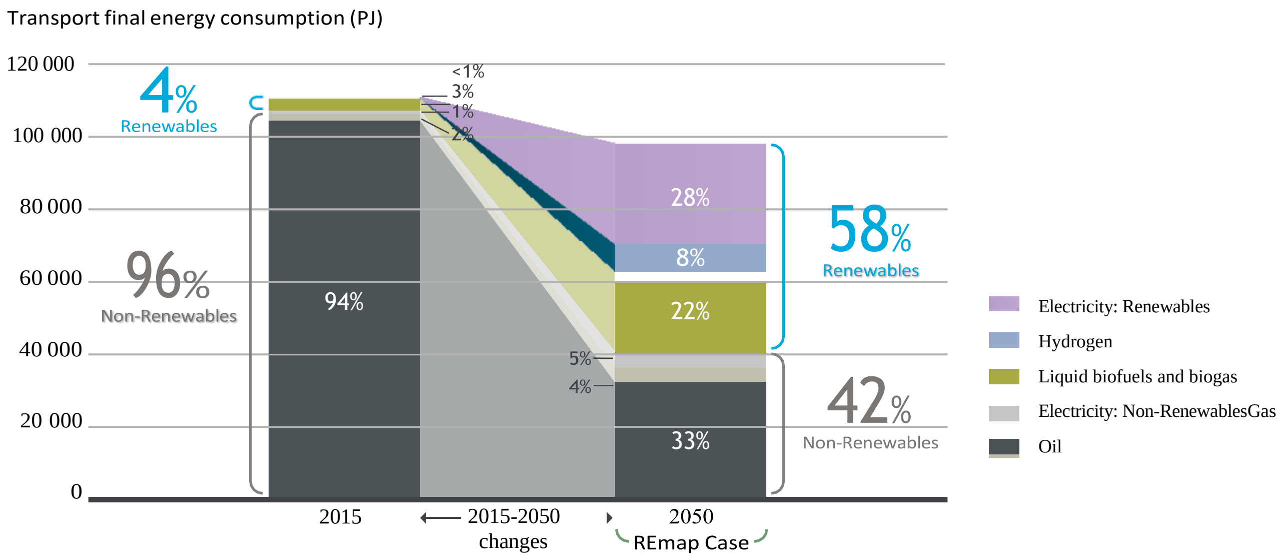
TRANSPORT

The transport sector lags behind in the energy transition. Globally, the share of renewable energy in this sector is very small at just 4% in 2015 (Figure 6). Use of renewables is dominated by biofuels, mostly bioethanol and biodiesel, in certain countries. Electrification, one of the technologies that can help to decarbonise the sector if associated with renewable power generation, is also extremely limited: it has a share of just above 1%. Shipping and aviation have also made comparatively little progress.

Analysis shows that the combination of low-carbon technologies proposed in the REmap Case can cut transport emissions to just 3 Gt of CO_2 annually by 2050, which represents a 70% reduction compared to current policies in the Reference Case. On its own, the transport sector would be responsible for 30% of emission cuts (compared to the Reference Case).

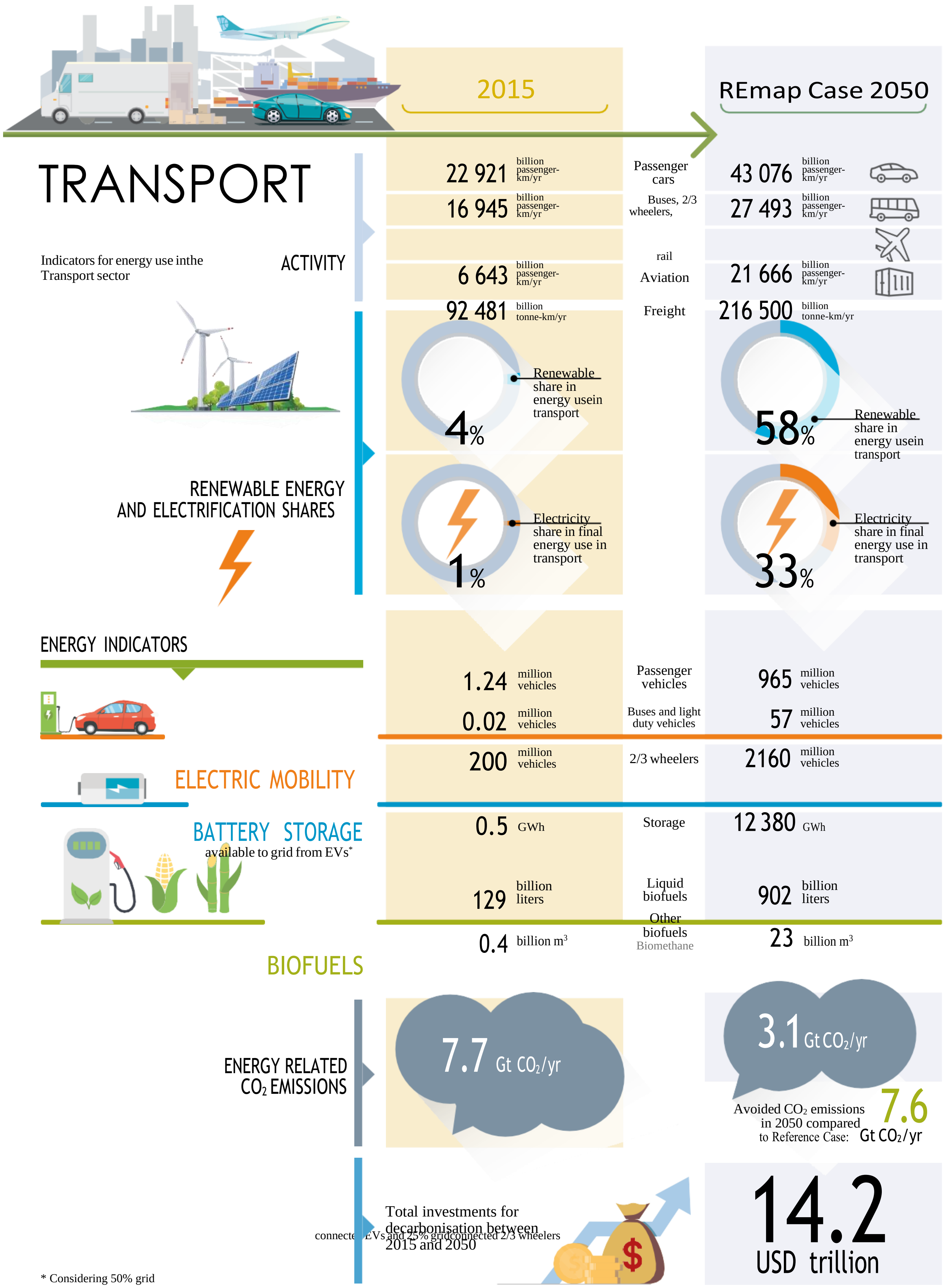
Figure 9. Transforming energy demand in the transport sector

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



The transport sector is dominated by fossil fuels and needs to undergo a profound transformation.

Figure 10. Infographic Transport



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 2015. The share of electricity in all of transport sector energy rises from just above 1% in 2015 to 33% in 2050, 85% of which is renewable. Biofuels increase their share from just below 3% to 22% in the same period.

Under the REmap Case, in absolute terms, total liquid biofuel production grows from 129 billion litres in 2015 to just over 900 billion litres in 2050. Nearly half of this total would be conventional biofuels, whose production would more than triple, requiring significant upscaling. Theother 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. The steep increase in biofuel production requires careful planning that fully considers the sustainability of biomass supply.

New energy sources, in combination with information and communication technologies (ICT), are changing the entire transport industry. As performance improves and battery costs fall, sales of electric vehicles, electric buses and electric two- and three-wheelers are growing. In 2017 around 3 million electric vehicles were on the road. Under the REmap Case, the number would increaseto over 1 billion by 2050. To achieve this, most of the passenger vehicles sold from about 2040 would need to be electric. Under the REmap Case, while about 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.

Another option that the REmap Case explores is the use of hydrogen as a transport fuel which can used for example, in vehicles powered by fuel cells. This option is particularly relevant because variable renewable electricity generation is expanding and the production of hydrogenfrom renewable power may provide an important option in efforts to meet demand flexibly andexpand renewable power generation. 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 by 2050. Around USD 3.4 trillion would be needed to develop the biofuel (predominantly advanced biofuels) and hydrogen industries. The balance would be needed to develop electrification and energy efficiency.

BUILDINGS

The building sector currently covers a residential and commercial floor area of 150 billion square metres (m^2), but this is projected to increase to 270 billion m^2 by 2050. Buildings make a significant contribution to global emissions and need to play a central role in efforts to reduce them. Although this is widely recognised, the sector has so far done little to promote the energy transition. In 2015, globally, an estimated 36% (including traditional biomass) of the energy used in buildings was renewable (Figure 12).

Electricity demand in the building sector is projected to increase by 70% by 2050, despite improvements in appliance efficiency, because of strong growth in electricity demand (particularly in emerging economies) and increases in the electrification of heating (using heat-pumps and seasonal storage).

The REmap Case considers deployment of highly efficient appliances, including smart home systems with advanced controls for lighting and heating, improved heating and cooling systems, better insulation, replacement of gas boilers by heat pumps and other efficient boilers, and retrofitting

Figure 11. Infographic Buildings

BUILDINGS

Indicators for energy use in the Buildings sector

ACTIVITY

2015		REmap Case 2050
144 million m^2	Total building stock floor area	269 million m^2
2.2 billion	Number of households	3.2 billion

RENEWABLE ENERGY AND ELECTRIFICATION SHARES

2015		REmap Case 2050
36%	Renewable share in energy use in buildings	77%
31%	Electricity share in final energy use in buildings	56%

RENEWABLE ENERGY INDICATORS

	2015		REmap Case 2050
BIOMASS	568 million units	Traditional cookstoves	0
	48 million units	Modern cookstoves	867 million units
	4 EJ/yr	Heat	7.6 EJ/yr
SOLAR THERMAL	622 million m^2	Collector area	6 299 million m^2
GEOTHERMAL	0.30 EJ/yr	Heat	1.76 EJ/yr
HEAT PUMPS	20 million units	Heat Pumps	253 million units

ENERGY RELATED CO_2 EMISSIONS

Avoided CO_2 emissions in 2050 compared to Reference Case: 2.3 Gt CO_2/yr

INVESTMENT

Total investments for decarbonisation for the period

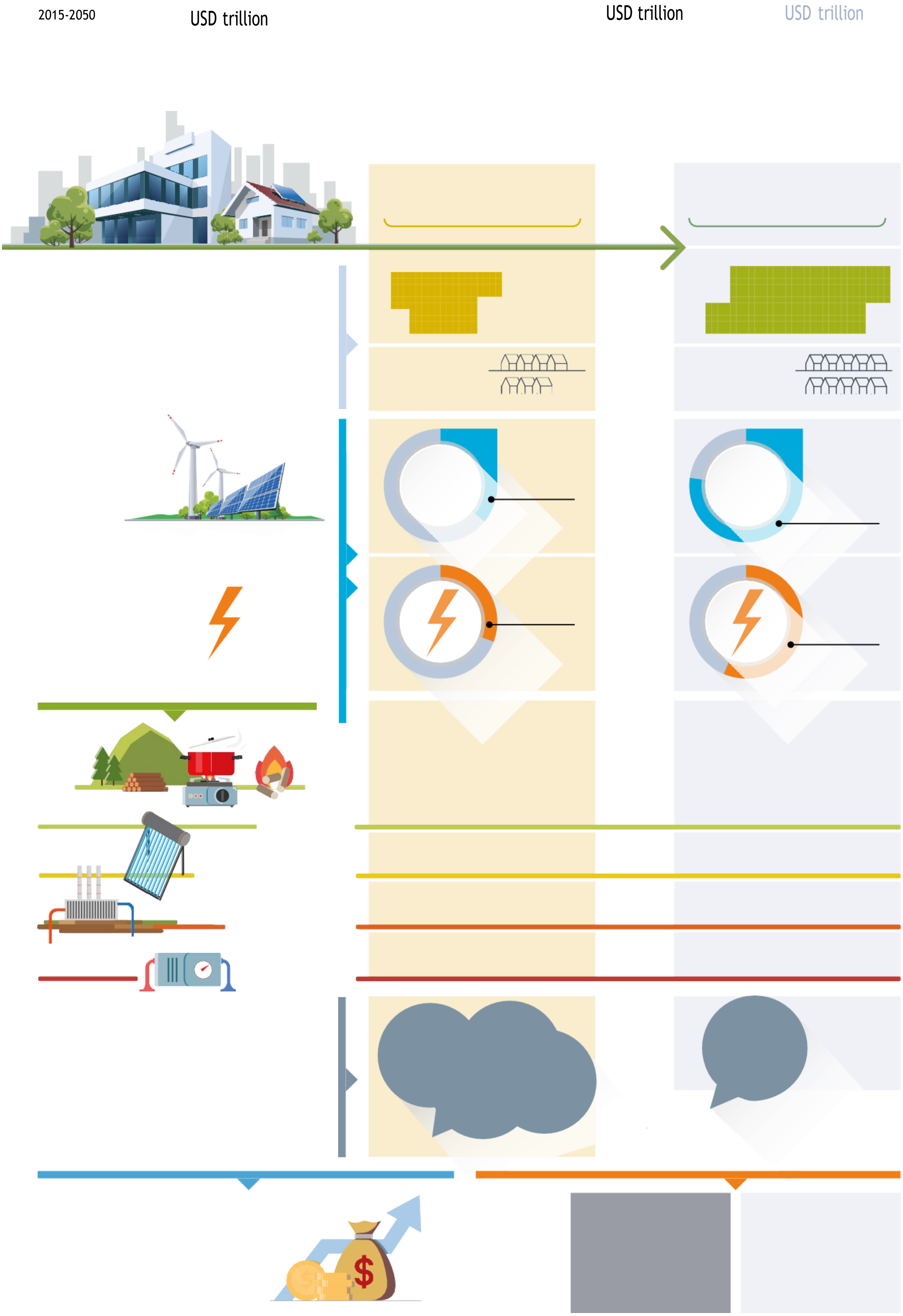
39.6

STRANDED ASSETS

for the period 2015-2050

Delayed Policy Action 10.8

REmap Case 2050 6.6


2015-2050
USD trillion
USD trillion
USD trillion

of old and new buildings to make them energy efficient. **Under the REmap Case, these measures would require a cumulative investment of USD 38 trillion between by 2050. In addition, USD 1.6 trillion would be required for renewables deployment in buildings.**

A significant increase in the share of modern renewables (excluding traditional uses of biomass) for heat and other direct-use must take place. The largest increase is in solar thermal systems,which would increase total collector area ten-fold, from around 600 million m^2 to over 6 000 million m^2.

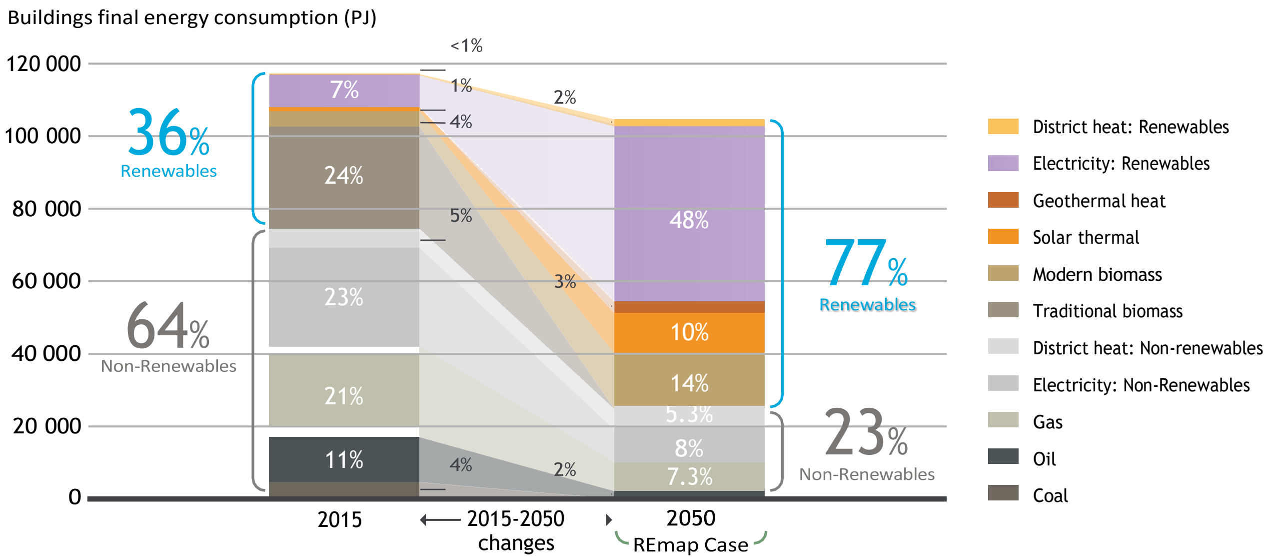
Heat pumps are also poised to play a critical role. Their use to heat buildings can be significantly expanded. Heat pumps achieve energy efficiencies three to five times higher than boilers and can be powered by renewable electricity. Under the REmap Case, the number of heat-pump units in operation would increase from around 20 million today to over 250 million units in 2050. Theywould supply 27% of the heat demand in the building sector. Efficient and clean district energysystems would provide 16% of building heat demand, more than double today's level.

The shift in cooking technologies from fuel to electricity will also promote renewables, due to the high share of renewable power in 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 (72% under the REmap Case) will be spent on making buildings more energy efficient.Early action is required to avoid stranded assets and meet future re-investment needs.

Bioenergy will remain the largest renewable fuel source in buildings. It will meet about 30% of heating and cooking demand. This implies a three-fold increase relative to today's levels. Use of biogas will also increase.

Figure 12. The increasing use of electricity in buildings and the decline of fossil fuels
Breakdown of final energy consumption in the building sector, by source (PJ/yr)



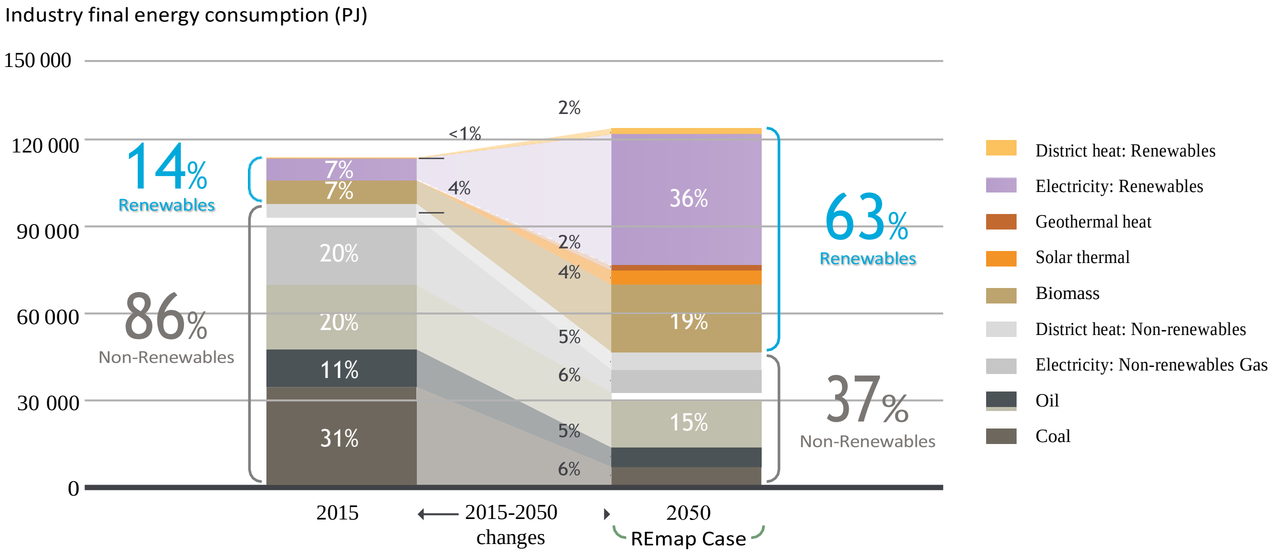
Modern renewable energy in the building sector needs to increase significantly. Up to three-quarters of energy consumption in buildings could be supplied by renewables. Electricity will supply almost 56% of the sector's energy demand.

INDUSTRY

To date, the industry sector has been the biggest laggard with respect to the energy transition. In 2015 renewables provided only around 7% of industry's direct energy use (i.e., excluding electricity) (Figure 13). Most of this was bioenergy. Electricity supplied almost 27% of the energy consumed by the sector.

Figure 13. A diverse energy mix with sizeable bioenergy demand

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

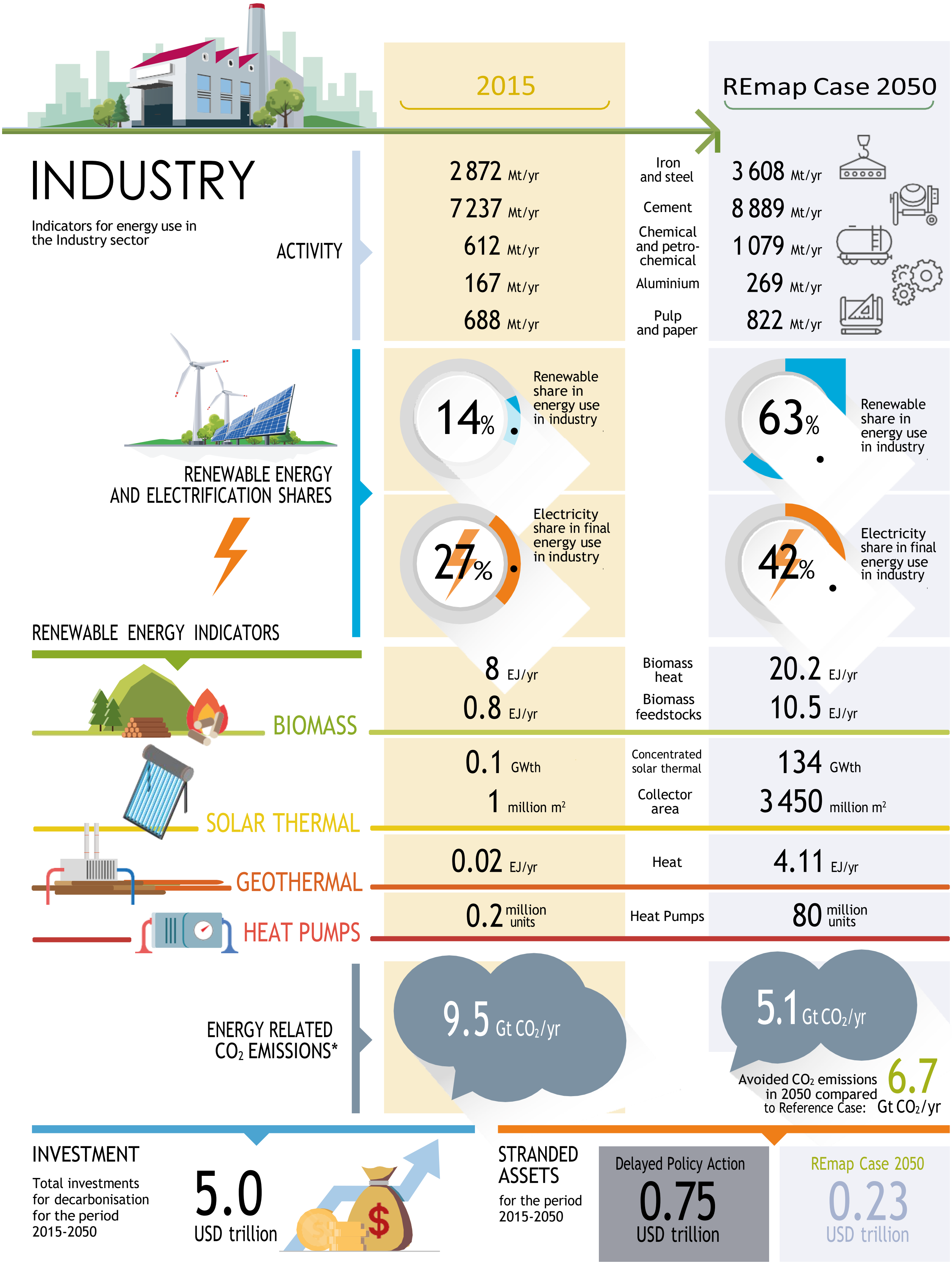


By 2050 renewable energy use in industry needs to grow by more than four times. Biomass and renewable electrification will have a prominent role.

In terms of emissions, the industrial sector is the second-largest emitter of energy-related CO_2. It is responsible for a third of emissions worldwide. Despite the fact that IRENA's REmap Case reduces the sector's emissions by more than half by 2050 (compared to existing national plans),industry would still emit 5.1 Gt of CO_2 in 2050 (a little under half of which would be process related emissions). Under the REmap Case, industry becomes the largest source of emissions; its sharerises from 29% to 46% of annual emissions by 2050. 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 more than double. An additional USD 2.8 trillion (compared to the Reference Case) would be required for total investments during the period to 2050 amounting to USD 5 trillion.

Figure 14. Infographic Industry



* Includes process emissions

Under the REmap Case, industry must increase the share of renewable energy in direct-uses and fuels to 48% by 2050. If renewable electricity is included the share would increase to aroundtwo-thirds. Bioenergy sources will be the highest contributor, largely based on residues used for direct heat and combined heat and power (CHP). In percentage terms, the largest increaseswill be in solar thermal heat for low-temperature processes and also heat-pumps for similar low-temperature heat needs. Under the energy transition, electricity should meet 41% of industry's energy needs by 2050.

In percentage terms, the largest growth will be in 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 3.4 billion m^2 of solar thermal collectors (concentrated and flat plate), providing 7% of industry's heat demand. By 2050 80 million units heat pumps will 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 will remain critical. Its use will increase the most in absolute terms. Bioenergy will be drawn from biomass residues, industry waste, and feedstocks for petrochemicals. 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 will also play an important role in the sector; the use of hydrogen derived from renewables grows to 7 EJ by 2050. In industry, it will principally be used to replace natural gas and produce chemicals.

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 process efficiency, adopt demand side management solutions, introduce highly efficient motors, develop material recycling, and strengthen waste management.

POWER

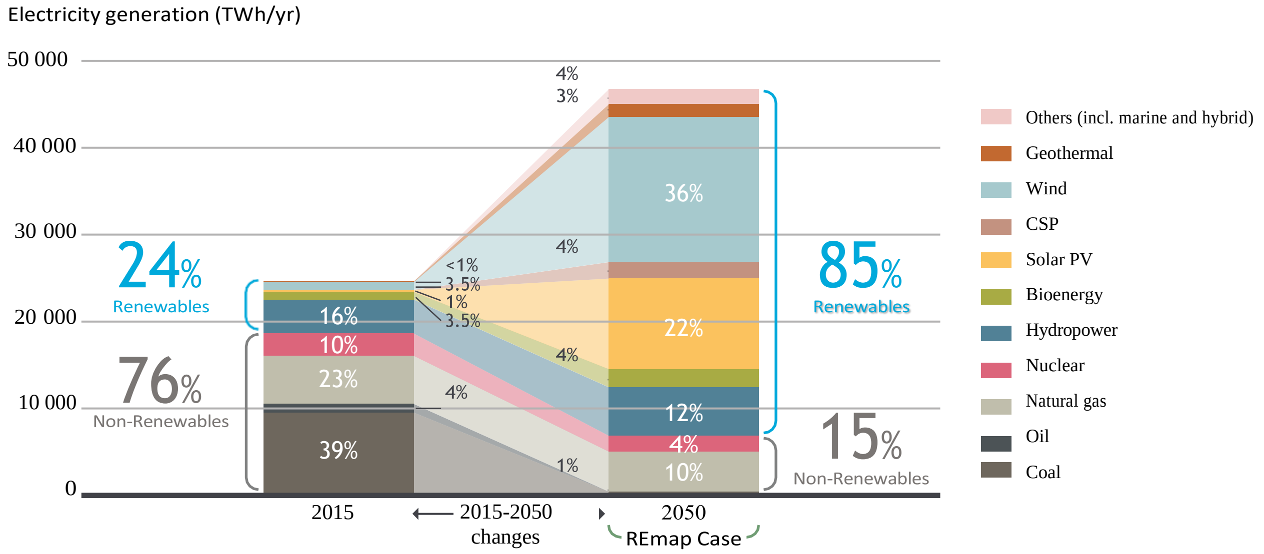
To deliver the energy transition at the pace and scale needed will require the almost complete decarbonisation of the electricity sector by 2050. This can be achieved by using renewables, increasing energy efficiency, and making power systems more flexible.

Under the REmap Case, electricity consumption in end-use sectors would double by 2050 (relative to 2015 levels) to over 42 000 TWh, while the carbon intensity of the power sector would decline by 85% (Figure 15). By 2050 the share of renewable energy in generation would be 85%, up from an estimated 25% in 2017. Solar and wind capacity will lead the way, rising from 800 GW today to 13 000 GW by 2050. In addition, the output of geothermal, bioenergy and hydropower would increase by 800 GW over the period. Annual additions of installed renewablepower capacity would double to around 400 GW per year, 80% of which will be variable generationtechnologies such as solar and wind. Decentralised renewable power generation grows from just 2% of total generation today to 21% by 2050, a ten-fold increase. **No new coal plants should becommissioned and 95% of coal plants in operation today should be phased out.**

Investment in new renewable power capacity should increase to almost USD 500 billion per year over the period to 2050. To create a power system with 85% renewable power will require investments in infrastructure and energy flexibility of another USD 500 billion per year, or around

USD 250 billion per year more than business-as-usual (the Reference Case). **In all, investment in decarbonisation of the power system will need to reach an average of nearly USD 1 trillion per year to 2050.**

Figure 15. The rising importance of solar and wind energy in the power sector
Breakdown of electricity generation, by source (TWh/yr)

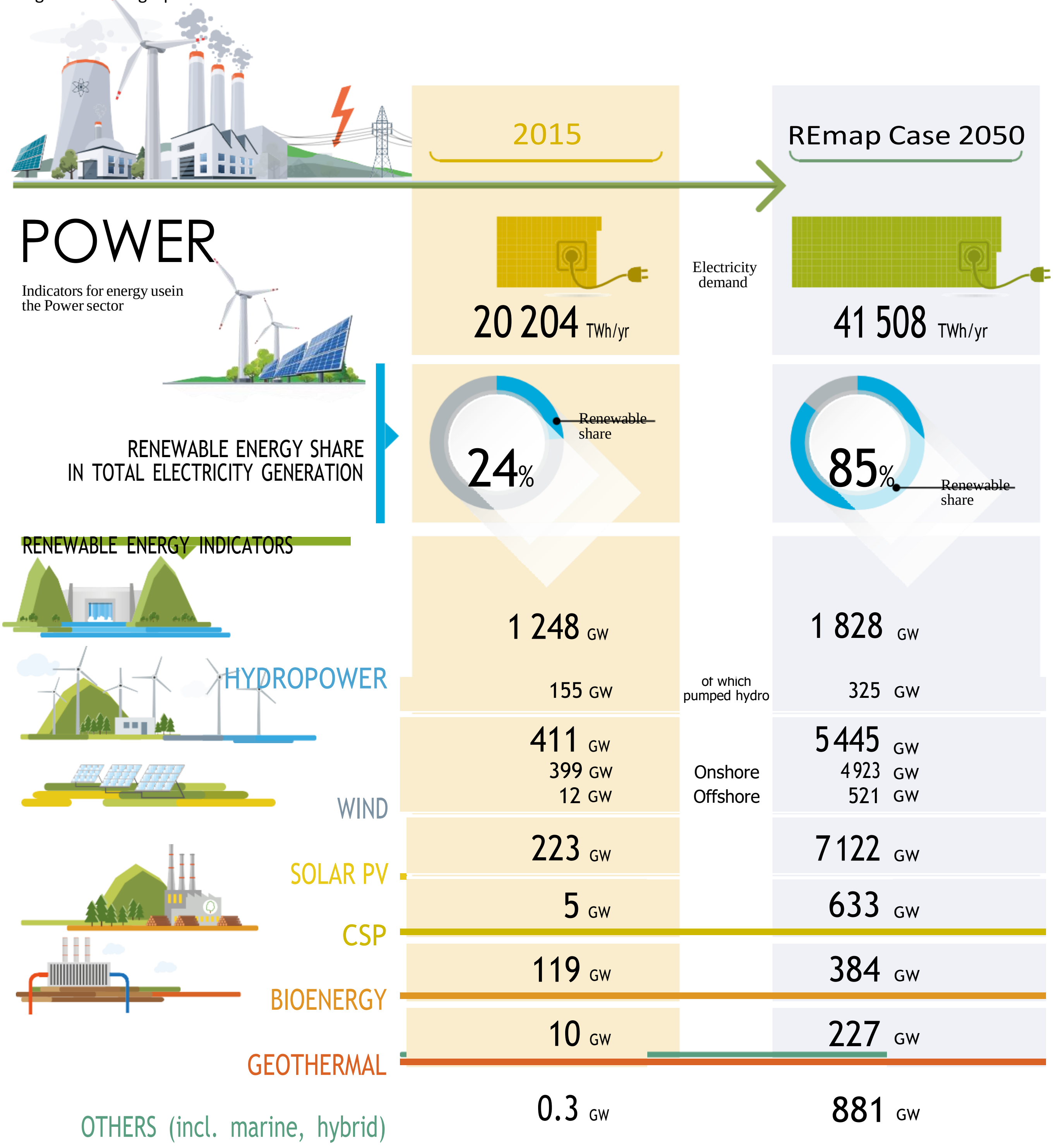


Gross power generation will almost double with renewable energy providing 85% of electricity.

For power generation using renewables, the Reference Case would require total investment of USD 8 trillion between 2015 and 2050. The REmap's decarbonisation options would double that to nearly USD 16 trillion. Much of the additional investments are required to deploy variable renewables such as wind onshore (33%), solar PV (31%), and concentrated solar power (CSP) (12%). As the share of renewable energy in electricity generation rises, investments will be needed for storage, transmission and distribution capacity, and for flexible generation and demand-response. Between 2015 and 2050, investments in these areas would add an estimated USD 9 trillion under the REmap Case (relative to the Reference Case). This investment would allow the system to accommodate 62% VRE while ensuring an adequate, stable and reliable electricity supply. Cumulatively, the investment needs of the power sector (beyond generation capacity) reach USD 18 trillion by 2050 under the REmap Case. This is double the investment that is projected under the Reference Case.

In terms of fossil fuel power generation, between 2015 and 2050 the REmap Case would save around USD 2 trillion compared to the Reference Case, because it accelerates use of renewables and promotes higher efficiency.

Figure 16. Infographic Power



* This includes investments needed for transmission and distribution grid expansion,increased generation flexibility, electricity storage.

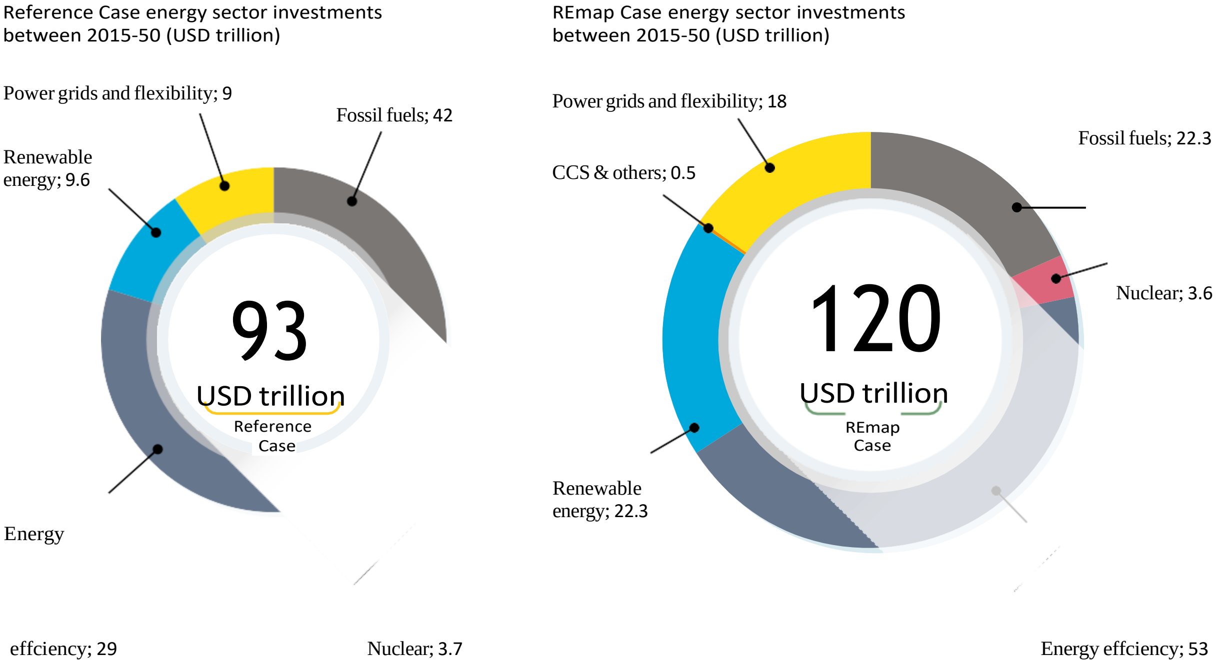
COSTS, INVESTMENTS AND REDUCED EXTERNALITIES
OF THE ENERGY TRANSITION

The energy transition is technically feasible and economically beneficial, but will require substantial additional investment in low-carbon technologies compared to current and planned policies (the Reference Case). Between 2015 and 2050, cumulative investment in the energy system will need to increase from USD 93 trillion (under the Reference Case) to USD 120 trillion (under the REmap Case) (Figure 17). **Additional investment of USD 27 trillion over the period will be needed.**

Under the Remap Case, investments in renewable energy and energy efficiency would composethe bulk of total energy investments (USD 75 trillion). These would nearly double relative to theReference Case. USD 20 trillion would be diverted from investment in fossil fuels to investment in renewable energy and efficiency. Additionally, USD 18 trillion would need to be invested in the power grid and in energy flexibility. **In total, between 2015 and 2050, the global economy would need average investments equivalent to some 2.0% of global GDP per year in decarbonisation solutions, including renewable energy, energy efficiency and other technologies.**

Figure 17. Investment will need to shift to renewable energy and energy efficiency

Cumulative investment - Reference and REmap cases, 2015-2050 (USD trillion)

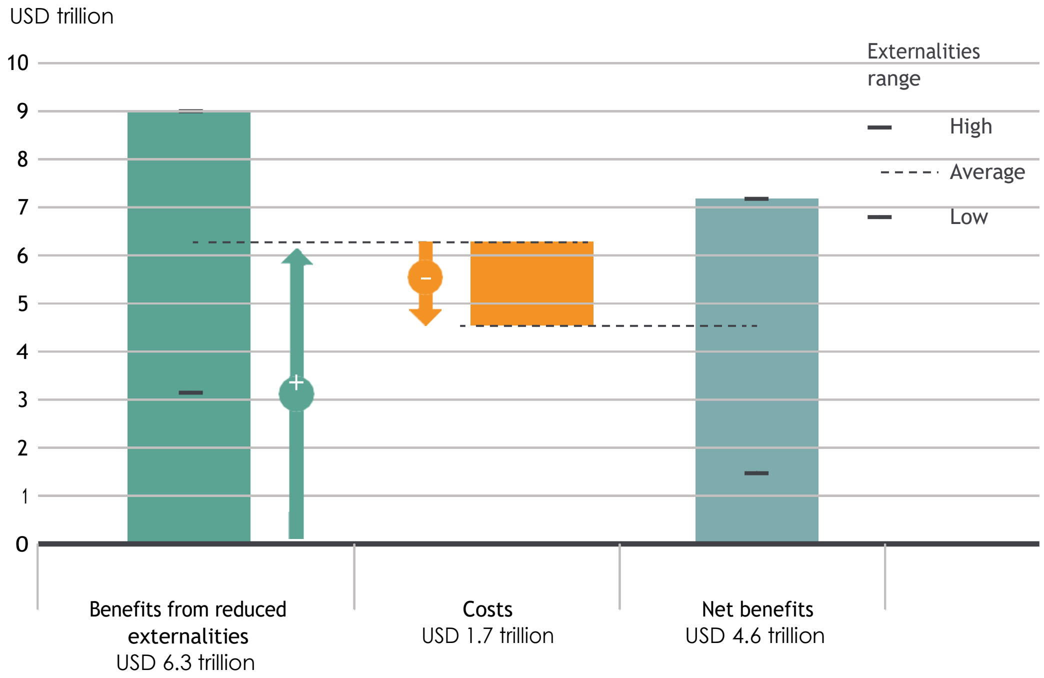


Under the REmap Case, cumulative investment of USD 120 trillion must be made between 2015 and 2050 in low-carbon technologies, averaging around 2.0% of global GDP per year.

Combined with reduced fuel expenditures, these increased 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 1.7 trillion in 2050, or about 0.5% of global GDP in that year. The increase is largely due to infrastructure investments.

However, cost savings significantly outweigh the increase in energy system costs. Cost savings would be made, in particular, because air pollution would decline, lowering health costs, and environmental damage due to CO_2 would lessen. 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 6 trillion annually by 2050, an amount that is over three times larger than the additional cost of decarbonisation. If the higher end estimate is used, then cost savings would be as much as five times larger than the additional cost of decarbonisation (Figure 18). Moreover,these economic benefits do not take into account the additional benefits of renewable energy deployment and energy efficiency, which include lower water consumption, job creation, and higher GDP. The analysis also suggests that there would be a general improvement in welfare (see global welfare discussion).

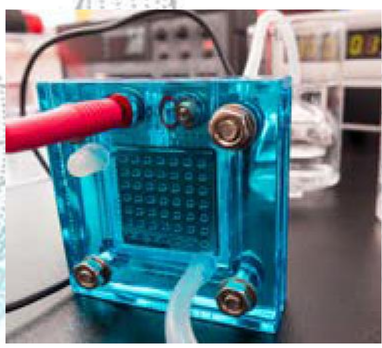
Figure 18. Reduced negative externalities far outweigh the costs of the energy transition
Annual costs of the energy transition set against reduced externalities (air pollution and CO_2 damage) - REmap Case compared to the Reference Case, 2050 (USD trillion)



Under the REmap Case, annual health and CO_2 benefits associated with the energy transition outweigh incremental costs by 2 to 5 times in 2050.

Energy subsidies and externalities cause many misconceptions about the costs of the energy transition. In 2016, subsidies to fossil fuels exceeded those to renewables by a factor of between two (not counting externalities) to thirty-eight (including externalities) (Coady *et al.*, 2015; IEA, 2017). IRENA estimates that supply-side renewable energy subsidies will be required in the early stages of the energy transition in different sectors to drive deployment and reduce costs, given the lack of adequate pricing of the externalities of fossil fuels (*e.g.*, local pollutant and CO_2 emissions) but as renewable options become cheaper than fossil fuel options, these subsidies decline and are eventually replaced by net-economic benefits (before taking into account the cost of pollutants,which would result in even larger benefits). Reflecting the greater progress in deploying renewablesin power generation, this sector currently accounts for the largest share of subsidies. However,the cost of power generation subsidies will decline rapidly in many countries, because renewable energy technologies are already, or will soon become, cost competitive. However, as other sectors are decarbonised, subsidies to accelerate deployment and drive down costs in the transport and industry sectors grow as they start to decarbonise.

To reduce the risk of stranded assets, action has to be taken quickly and investments must be channelled into the right energy technologies. The slow progress of emission mitigation to date means that the adoption of an emissions mitigation path in the REmap Case will stillresult in stranded assets worth more than USD 11 trillion. 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 by another 15 years would make the energy transition more expensive and would double the assets stranded between today and 2050. In addition, delaying action could make it necessary to adopt costly technologies to remove carbon from the atmosphere (negative emission technologies, such as bioenergy with carbon capture and sequestration) in order to stay within the emissions envelope (for more information about the carbon budget assumed for this analysis, please see IEA and IRENA, 2017).



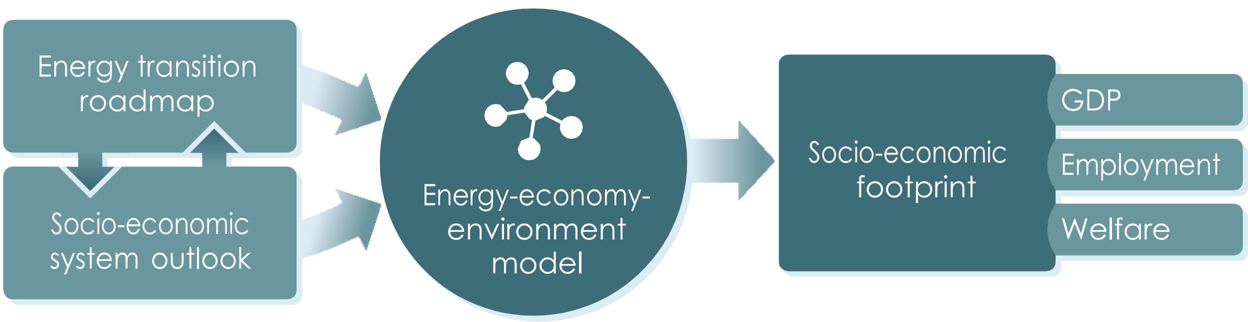
SOCIO-ECONOMIC BENEFITS OF THE ENERGY TRANSITION

The need to bring economic and environmental objectives into closer alignment, and in particular to reduce the climate impacts of a fossil fuel-based world economy, is prompting a profound restructuring of the energy system. This change is made possible by increasingly mature and competitive renewable energy and energy efficiency technologies that change the ways in which electricity, heat and fuels are produced and consumed. However, the energy transition cannot be considered in isolation from the broader socio-economic system. In fact, the changes in the energy system triggered by the REmap transition roadmap have impacts throughout the broader economy.

The close interplay between the energy sector and the economy alters the socio-economic footprint and generates a number of benefits in terms of GDP, employment and human welfare (Figure 19). The analysis of the drivers and dynamics underpinning this outcome provides valuable insights into how the overall transition process could be improved.

As is the case with any economic transition, there will be regions and countries that fare better than others due to diverging structures, capacities and dynamics. Policymakers can help to make the transition process a just one by initiating economic diversification investments, supporting initiatives that help build and strengthen domestic supply chains capable of responding to new economic opportunities, adopting social protection measures for people dependent on declining industries (including fossil fuels), and by supporting the transition in the context of energy access (see Box 2).

Figure 19. Obtaining the socio-economic footprint from a given combination of an energy transition roadmap and a socio-economic system structure and outlook



Box 2 Energy access and the transition

In 2000, 1.7 billion people lacked access to electricity. While 1.2 billion people have gained access since then, 1.1 billion people continue to live without electricity (95% of them live in Sub-Saharan Africa and Asia). Based on current trends and policies, 680 million people wouldstill lack access to electricity in 2030 (80% of them in rural areas of sub-Saharan Africa), implying failure to achieve the United Nations (UN) Sustainable Development Goal 7 (SDG 7). To provide electricity for all by 2030 would require annual investment of some USD 52 billion per year in power generation and infrastructure, equal to 3.4% of average annual global energy sector investment.

To realise the energy transition successfully will require to change the entire socio-economic system, and make inclusiveness one of its pillars. Social fairness and justice are among the most important ideas that will drive energy access during the transition. But they are relevant for more pragmatic reasons too. If access is not universal, the transition will remain incomplete, and the disequilibrium in socio-economic organisation would ultimately undermine efforts to achieve global sustainability and climate goals.

Access in a transition context goes well beyond energy access:

- Access to services requires more integrated approaches that search for synergies between renewable energy and energy efficiency, and promote socio-economic activity including its welfare implications.
- Holistic planning is required to facilitate the organic evolution of infrastructures (off-grid, mini-grid, grid) and socio-economic structures, and to avoid stranding assets and resources that are needed and scarce.
- The transition will not be complete until all regions and communities have access to services. The energy implications of this position go well beyond providing basic energy to populations that still lack access to it. It requires planning for the full and universal integration of services.
- Financing also plays an important role in access. Novel business models and social financing initiatives already facilitate access, but further action is required in all public, private and community forums.

Cost reductions and advances in technology have enabled off-grid renewable energy solutions to become a mainstream option for expanding electricity access. The off-grid renewable energy sector has been transformed in the last decade. The private sector is increasingly engaged, driving business and financing technology innovations that bring down costs and make off-grid solutions more accessible to rural communities. Other enabling factors, such as payment digitisation and remote monitoring, are also contributing to the accelerated deployment of off-grid solutions.

Renewable energy solutions offer a clear pathway for accelerating progress towards SDG 7, as well as a more complete energy transition, in an affordable, environmentally-sustainable and equitable manner. Their role in national electrification strategies needs to be recognised and holistically planned so that the public and private sectors, financing institutions, communities and civil society can collectively transform energy services in underserved areas.

To further accelerate access to renewable energy requires an enabling environment. This needs to include well designed policies and regulations, customised business and financing models, adapted and appropriate technology solutions, capacity building, and dedicated platforms for sharing best practices and lessons learned. Gender, local community engagement and productive end-use support are equally important to the sustainability of projects and initiatives, and the achievement of fair outcomes.

The analysis presented in this section builds on IRENA's body of work focusing on measuring the economics and benefits of the energy transition and renewable energy employment (IEA and IRENA, 2017; IRENA, 2018d, 2017d, 2017g, 2017h). The analysis delves into macroeconomic variables to present the socio-economic footprint of the REmap roadmap, both at global and regional level, as deployed on the current socio-economic system.[2]

The main macroeconomic drivers used to analyse the GDP and employment footprints include investment, trade, tax changes, indirect and induced effects. In the case of employment, the 'consumer expenditure' driver combines the impacts from taxes, indirect and induced effects, while capturing other labour-related dynamic effects. In different regions, these drivers interact with region-specific socio-economic systems, leading to diverging transition outcomes.

The transition provides socio-economic benefits that go well beyond what GDP can measure. Regarding **employment** outcomes, details are also presented for the energy sector, and its components (*e.g.*, renewables, energy efficiency, grids upgrade and energy flexibility). A **welfare indicator** encompassing economic, social and environmental dimensions is used to quantify the broader transition impact. Financing the transition is a cornerstone of the socio-economic system's outlook. An analysis of the role of **finance** is presented, highlighting its interactions with the socio-economic system, as well as the potential finance-related transition barriers and how to address them.

2 To perform this analysis, the E3ME energy-economy model from Cambridge Econometrics has been applied. The E3ME is a global macro-econometric model with regional and sectorial resolution that captures the diverse interactions between the energy and economy systems.

GLOBAL GDP

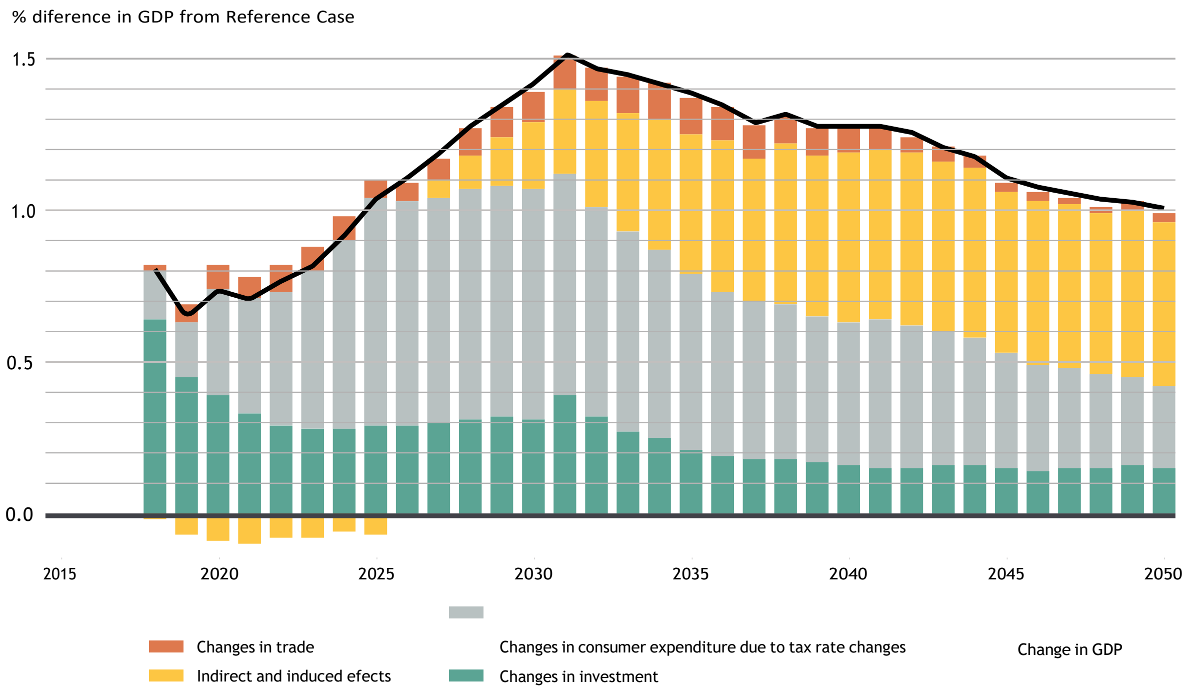
Across the world economy, GDP increases from 2018 to 2050 in both the reference and transition scenarios. However, the energy transition stimulates economic activity additional to the growth that could be expected under a business as usual approach. The cumulative gain through increased GDP from 2018 till 2050 will amount to USD 52 trillion.

The GDP transition footprint for the world is presented in Figure 20, which shows that the REmap energy transition has a consistently positive effect on global GDP between 2018 and 2050, compared to the reference scenario. The gain over the Reference Case is greatest in 2031, peaking at 1.5% of GDP, and then gradually narrows to 1.0% in 2050. The reference scenario has a compound annual growth rate between 2018 and 2050 of 3.0%. The per capita world average GDP for the transition scenario increases from 10,800 USD (in constant 2015 dollars) in 2018 to 22,400 USD in 2050. Figure 20 also quantifies the contributions to GDP of four major drivers (investment stimulus, trade effects, tax shifts and indirect/induced effects).

The first positive impact on GDP is due to a net investment stimulus in renewables, energy efficiency, grids and energy flexibility. First, changes in tax rates, mainly associated with carbon taxes and the phase-out of fossil fuels, boost GDP growth in the medium term. Second, after a dynamic time-lag, indirect and induced effects take over and have a positive impact on GDP in the second half of the energy transition (to 2050 and beyond). As expected global trade has a minor impact on the global GDP increase throughout the whole transition, given the intrinsic requirement of global trade being balanced in nominal terms.

Figure 20. The energy transition results in GDP growth higher than the Reference Case between 2018 and 2050

Relative difference of global GDP between the REmap Case and the Reference Case, 2018-2050



+0.31% compared to the Reference case in 2030

+0.15% compared to the Reference case in 2050

The **investment** stimulus is the main initial driver of improvement in global GDP during the energy transition. Over time, the relative contribution of investments to GDP growth declines. High values in 2018 steadily reduce over the first half of the transition period. This is explained by two factors. First, under the Reference Case, investment increases in later years, lowering the relative impact of the driver. Second, a small proportion of existing capacity is retired in the early years, so that most of the early investment in renewables is additional.

Figure 20 shows the net investment effect with respect to three main sub-drivers: (i) energy efficiency; (ii) the power sector, including generation, transmission and distribution (T&D) grids, and energy flexibility; and (iii) other investments in the economy, including investments required for upstream supply of fossil fuels, and the impact of crowding out of capital.

Net investment is initially dominated by investment in energy efficiency measures, although this contribution steadily declines under the REmap Case because it is expressed relative to investments that increase energy efficiency under the Reference Case. The impact of investment on GDP in the power sector is relatively small initially, because it measures the net effect of higher investment in renewables and lower investment in fossil fuel energy generation. Its contribution is rather steady and, under the REmap Case, increases in the second half of the period. This increase is due to investments in T&D and flexibility, which play a growing role in power sector investment over the period to 2050. The contribution of other investments in the economy is negative throughout the transition period due to foregone investments in upstream fossil fuels and the crowding out effect.

+0.10% compared to the Reference case in 2030

+0.03% compared to the Reference case in 2050

Global trade has a very small impact on GDP throughout the transition, because of the intrinsic requirement to balance global trade in nominal terms (imports in some regions are directly linked to exports in others). The small positive differences stem from the application of country-specific deflators to convert investment from nominal to real terms, which leads to some discrepancies between total imports and exports at a global scale. Trade, however, will have important impacts on GDP at regional level.

+0.76% compared to the Reference case in 2030

+0.27% compared to the Reference case in 2050

The tax rate driver is one of the main contributors to global GDP increases during the transition period. Its contribution is higher in the 2025–35 period, mainly due to carbon tax revenues which peak around 2030. Thereafter, some major economies (including China) start to cut carbon emissions rapidly, reducing government revenue from carbon taxes. On the negative side, loss of fossil fuel tax revenues (in countries that produce oil and gas) drags down tax revenue as global final demand for fossil fuels falls. As Figure 20 shows, this effect is completely compensated by the positive effects of tax rate changes.

+0.22% compared to the Reference case in 2030

+0.54% compared to the Reference case in 2050

Indirect and induced effects play the largest role in driving global GDP increases under the REmap Case in the secondhalf of the transition period. This reflects reduced expenditure on energy (particularly fossil fuels) and reallocation of this spending to other parts of the economy. Larger supply chains lead to increased indirect effects, and more wages lead to induced effects. As more money is reallocated from energy to other goods and services, benefits increase accordingly. The deployment of energy efficiency measures (which reduce energy consumption permanently), therefore, drives a steady increase in the contribution of indirect and induced effects.

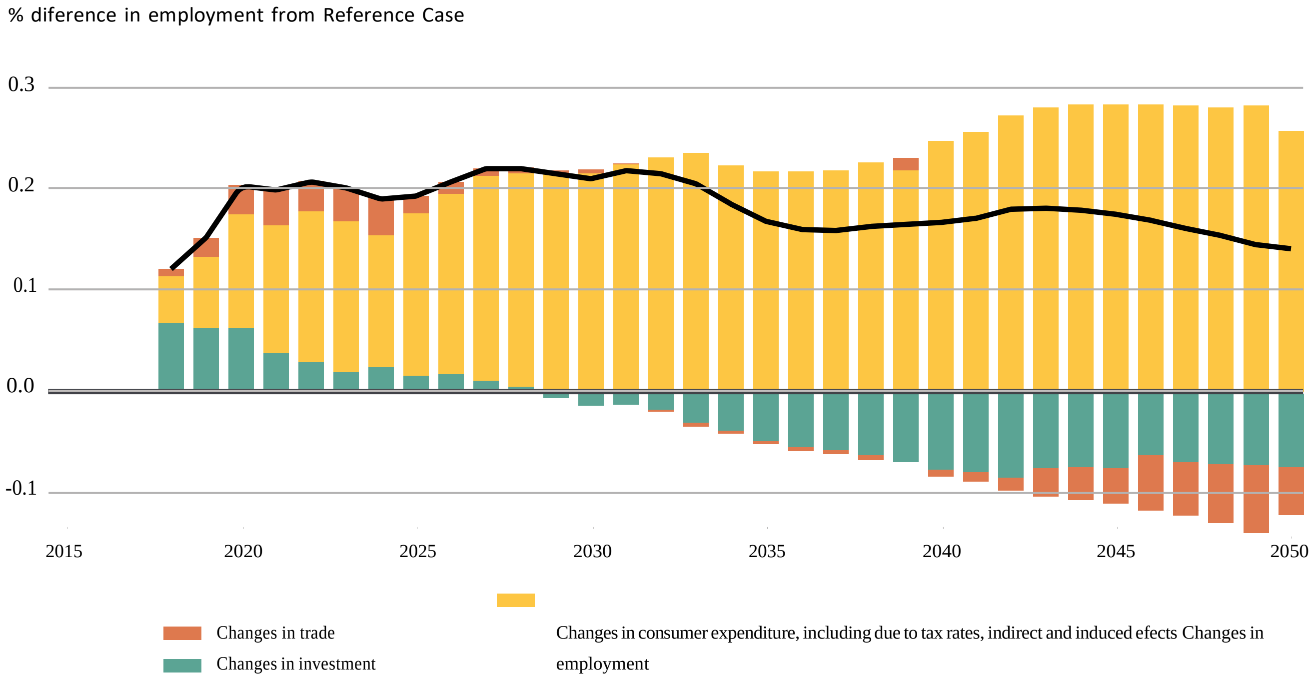
EMPLOYMENT IN THE GLOBAL ECONOMY

Across the world economy, employment increases between 2018 and 2050 under both the Reference and REmap cases. In the Reference Case, the compound annual growth during the period is 0.42% per year. In 2050, the aggregate gain in employment is around 0.14% higher under the REmap Case than under the Reference Case.

The employment effects are less significant than GDP effects (1.4% and 1%, in 2030 and 2050, respectively) because additional demand in the global economy also pushes up real wages. The additional wages available in the sector as a result of additional demand can be realised as increases in wages for all workers, or increases in the number of jobs (or a mix of the two). Historical trends show that wage effects tend to dominate, leading to smaller increases in employment than GDP. Figure 21 shows the drivers behind the stronger growth in employment under the REmap Case relative to the Reference Case. These include investment, trade and consumer expenditure.

Figure 21. The energy transition results in employment growth higher than the Reference Case between 2018 and 2050

Relative differences in global employment - REmap Case and Reference Case, disaggregated by three main drivers



-0.01% compared to the Reference case in 2030

-0.07% compared to the Reference case in 2050

Investment plays a positive role in increasing employment in the short term, contributing up to 0.06% in relative additional employment in 2020. Investments in energy efficiency dominate initially but their impact gradually falls over time. Investments in the power sector gradually emerge to become the dominant factor behind employment creation after 2040. In the power sector, the number of jobs created by renewables, T&D grids and energy flexibility is significantly greater than the number of jobs foregone in the fossil fuel power sector. However, the number of jobs lost as a result of foregone fuel extraction gradually increases during the period. Together with jobs lost from investment in other parts of the economy (partly due to crowding out), these job losses come to offset the positive investment contributions from 2030 onwards.

0.00% compared to the Reference case in 2030

-0.05% compared to the Reference case in 2050

Trade. Although in GDP terms global changes in trade are balanced, this is not the case for employment. The transition results in several shifts in trade: a sectoral shift (trade moves from fossil fuels to non-energy trade); a regional shift (importers/exporters change roles as their relative competitiveness is modified by transition impacts on relative energy prices and domestic supply chains); and a volume shift (where the volume of global trade can be modified). Each of these can significantly affect global trade, according to the characteristics of the energy transition and evolution of the socio-economic system. Under the REmap Case, trade initially promotes a positive but limited increase in employment; but this becomes negative after 2030 and significantly negative by 2050. This effect is due to two factors: trade in fossil fuels and non-energy trade. The latter is responsible for the employment downturn around 2030 and the overall negative impact on jobs by 2050.

+0.22% compared to the Reference case in 2030

+0.26% compared to the Reference case in 2050

Consumer expenditure is the dominant driver throughout the transition period, with three trends influencing the final results: (i) wage effects cause small decreases in employment in most years (in other words, increases in wage rates discourage firms from hiring workers); (ii) consumer expenditures continuously increase over the transition period, leading to higher demand for workers (to meet the additional demand for goods and services); and (iii) dynamic employment effects in the labour market, for example when firms pause hiring until they confirm that increases in production are sustained or are falling, or delay hiring in order to meet contractual notice periods, etc. These dynamic effects primarily reflect lagged outputs (*i.e.*, when an economy expands, employment will increase in later years rather than in the year when output started to grow).

GLOBAL ENERGY SECTOR EMPLOYMENT

The energy transition will increase employment not just in the broader economy, but specifically in the energy sector and in renewable energy. As shown in Figure 22, the global energy sector employed some 41 million people in 2016. This number includes jobs in the fuel supply and power sectors, but not in energy efficiency and grid enhancement,[3] for which no 2016 estimates are available. The number of fossil fuel jobs lost by the milestone years 2030 and 2050 is completely offset by the number of jobs created in renewable energy technologies. In addition, investments in energy efficiency measures and grid enhancement create further employment opportunities.

Under the Reference Case, a slight decline in fossil fuel employment by 2030 is compensated by a 28% increase in renewable energy jobs. By 2050, renewable energy adds more jobs, while the number of fossil fuel jobs remains roughly the same as in 2030.

Outcomes under the REmap Case are much better, because investment is higher in labour intensive technologies, including renewable energy and energy efficiency. In 2030, employment in renewables and energy efficiency together increases by around 70% (relative to the Reference Case), reaching 23.6 million and 25.3 million respectively. In fact, energy efficiency employs more people than either renewables or fossil fuel technologies. Under the REmap Case, total employment in the energy sector reaches 85 million in 2030, 25% more than under the Reference Case.

In 2050, total energy sector employment under both the Reference and REmap cases is lower than in 2030. To some extent, this is due to increasing labour productivity in all technologies. However, energy efficiency employment declines because much of the investment is front-loaded and then tapers off over time. Jobs in renewable energy, on the other hand, continue to increase under both the Reference and REmap cases, because of continued investments in the sector.

In sum, the analysis concludes that, compared to the Reference Case, by 2050 the energy transition would lead to a loss of 7.4 million direct and indirect jobs in fossil fuels, but a simultaneous gain of 19.0 million jobs in renewable energy, energy efficiency, and grid enhancement. Implementing the REmap Case would therefore result in a net gain of 11.6 million jobs.

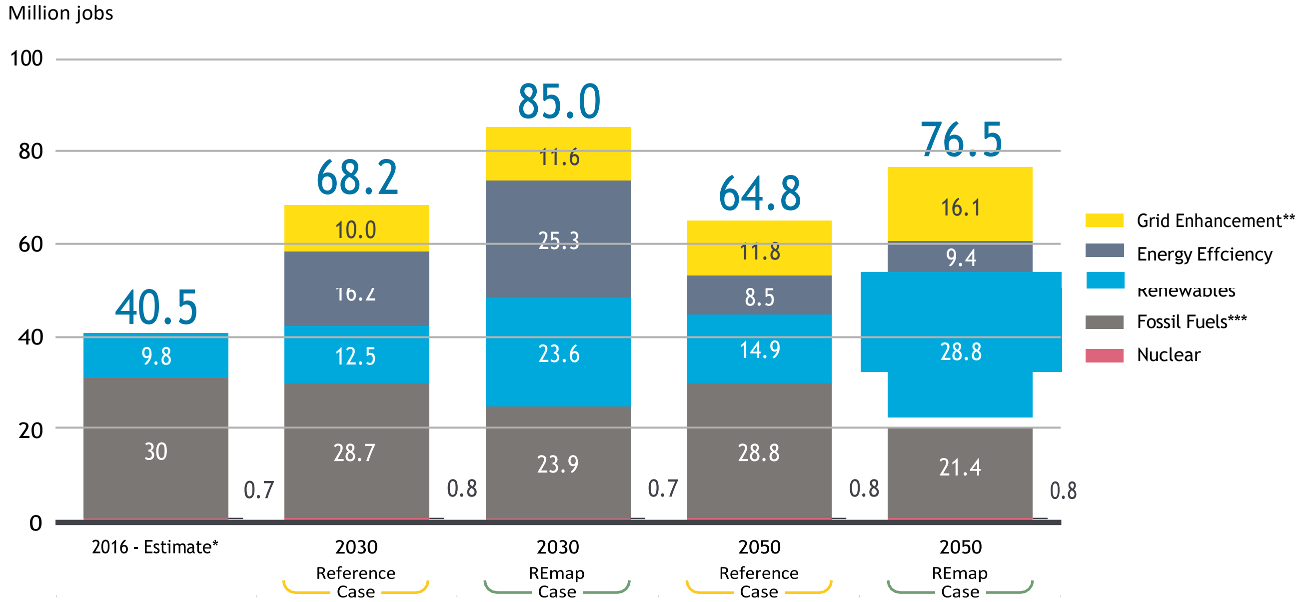
The results show that, under the Reference Case, employment in the renewable energy sector could reach 12.5 million by 2030 and 14.9 million in 2050, up from current levels of 9.8 million (see Figure 23) (IRENA, 2017d). However, employment in the renewable energy sector, under the REmap Case, could potentially double to reach 23.7 million by 2030 and 28.8 million by 2050.

Employment in the renewable energy sector in 2030 is expected to remain concentrated in the technologies used today (solar, bioenergy, hydropower and wind), with minor shifts depending on circumstances. Most renewable energy employment under the REmap Case would be in bioenergy (9.1 million jobs by 2030 and 11.3 million jobs by 2050), solar (8.5 and 11.9 million, respectively), hydropower (3.8 and 3.6 million, respectively) and wind (2.2 and 2.0 million, respectively).

3 Grid enhancement includes transmission and distribution systems and investments in energy flexibility that enable renewable energy to be integrated in the power system.

Figure 22. The energy transition would generate over 11 million additional energy sector jobs by 2050

Employment in the overall energy sector, 2016, 2030 and 2050 (million jobs)



* Estimates for jobs in energy efficiency and grid enhancement are not available for 2016.

** The jobs in grid enhancement make reference to the jobs for T&D grids and Energy Flexibility, created in thedevelopment, operation and maintenance of infrastructure to enable the integration of RES into the grid.

*** Includes all jobs in the fossil fuel industry including in their extraction, processing and consumption.

OCCUPATIONAL REQUIREMENTS

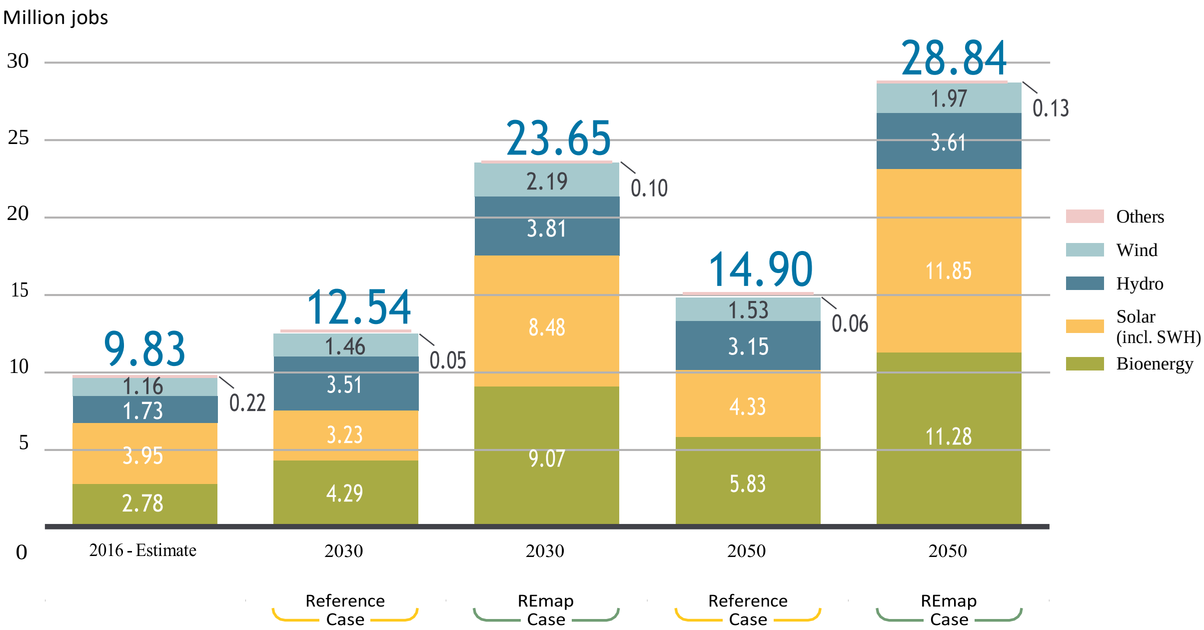
Depending on the technology, jobs will be distributed along different segments of the value chain. The chain includes equipment manufacturing, construction and installation, operation and maintenance, and (in the case of bioenergy) fuel supply. A detailed understanding of the occupational requirements of renewable energy technologies is required to plan for changes in the demand for skills during the transition. IRENA's reports on Leveraging Local Capacity have analysed the types and number of workers that will be needed in the solar PV and onshore and offshore wind industries (IRENA, 2018d, 2017f, 2017g). Building on these reports, it has estimated how many workers in different occupational groups will be required in 2030 and 2050 to achieve the Energy transition.

Renewables create jobs with a wide range of occupational and skills requirements. Around two-thirds of the jobs fall into the category of 'workers and technicians'. Another 16% are 'experts' (who broadly require tertiary education), and 14% are 'engineers and higher degrees' (requiring post-graduate qualifications). The remaining 3% are 'marketing and administrative personnel'.

As indicated, jobs in some traditional energy sectors will be lost as the transition to sustainable energy unfolds. With adequate re-training and other transition assistance, a proportion of this workforce can be absorbed by the renewable energy and energy efficiency sector, helping to meet the demand for skills. A deeper analysis of the occupational requirements of renewable energy technologies reveals that the managerial and technical skills and competencies of the oil and gas workforce are valued in the renewable energy sector. Workers and technicians with expertise in

Figure 23. The energy transition would generate 14 million additional jobs in renewable energy by 2050

Renewable energy employment by technology (million jobs)



constructing support structures for offshore oil and gas sites, for instance, can help to construct foundations and substations for offshore wind turbines. Similarly, large scale solar PV can benefit from the skills of engineers and experts with experience of setting up traditional power plants.

However, energy related jobs are not likely to be created and lost in the same areas and at the same time. Although the transition offers clear net employment gains, there is also a need for adjustments as the transition unfolds. This is particularly the case in countries and regions where many livelihoods depend on the fossil fuel sector. A pro-active just transition policy helps minimise socio-economic disruptions and promotes economic structures that allow countries to maximise benefits arising from the transition.

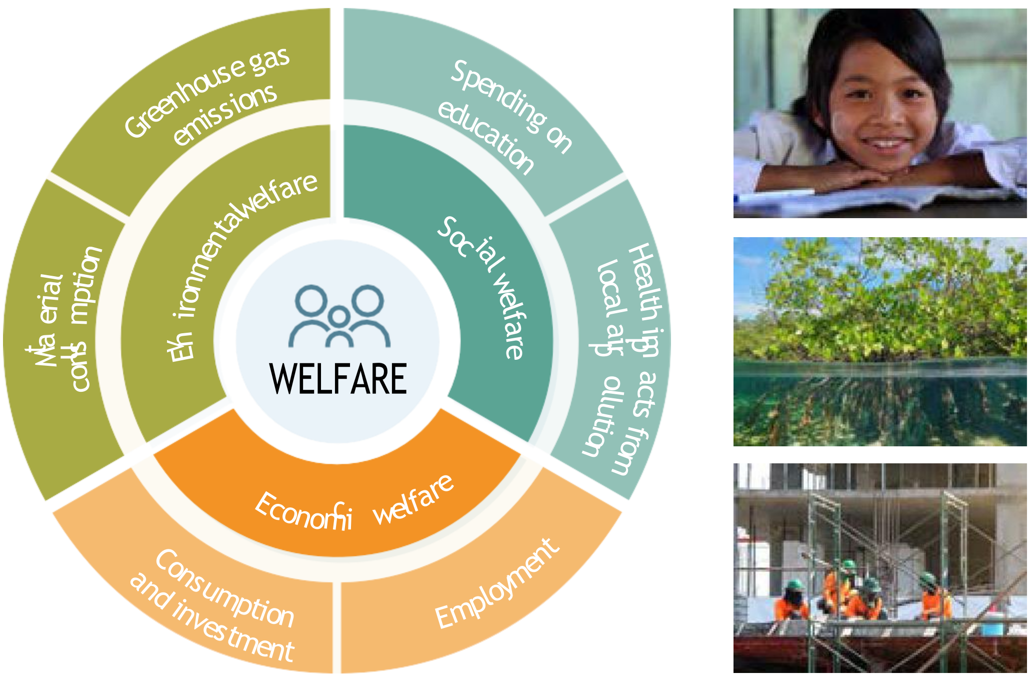
GLOBAL WELFARE

The energy transition generates broader socio-economic benefits, in addition to higher GDP and employment. GDP fails to capture human well-being, which includes health, education and the environment. As a result, focusing only on GDP may hamper movement towards truly sustainable and inclusive development. The welfare indicator in this analysis adopts the widely accepted three dimensions of sustainable development: economic, socialand environmental (IRENA, 2016).

The **economic dimension** is measured by total employment and by consumption plus investment (*i.e.*, current expenditure plus the future benefits of improved capital stock). The **social dimension** is a proxy for human capital, considers total (public and private) expenditure in education, and (reduction of) health impacts from air pollution. The **environmental dimension** focuses on (reduction of) GHG emissions and the depletion of natural resources through consumption of materials (measured in direct material consumption of minerals and biomass for food and feed, excluding fossil fuel energy resources).

This analysis obtains six sub-indicators, two for each dimension of sustainability (see Figure 24) which are aggregated into an overall welfare indicator. The weighting of each sub-indicator should ideally depend on the relative importance that a society gives to each, but for this analysis we weighted all sub-indicators equally.

Figure 24. Components of the welfare indicator used in this analysis



Source: Based on IRENA, 2016

The transition outlined by REmap improves human well-being in ways that GDP is not able to capture, and thus the increases in welfare are larger than those in GDP. Figure 25 directly compares the global welfare indicator (and the contribution from each of its sub-indicators), with the relative increase in GDP, for the REmap transition in years 2030 and 2050.

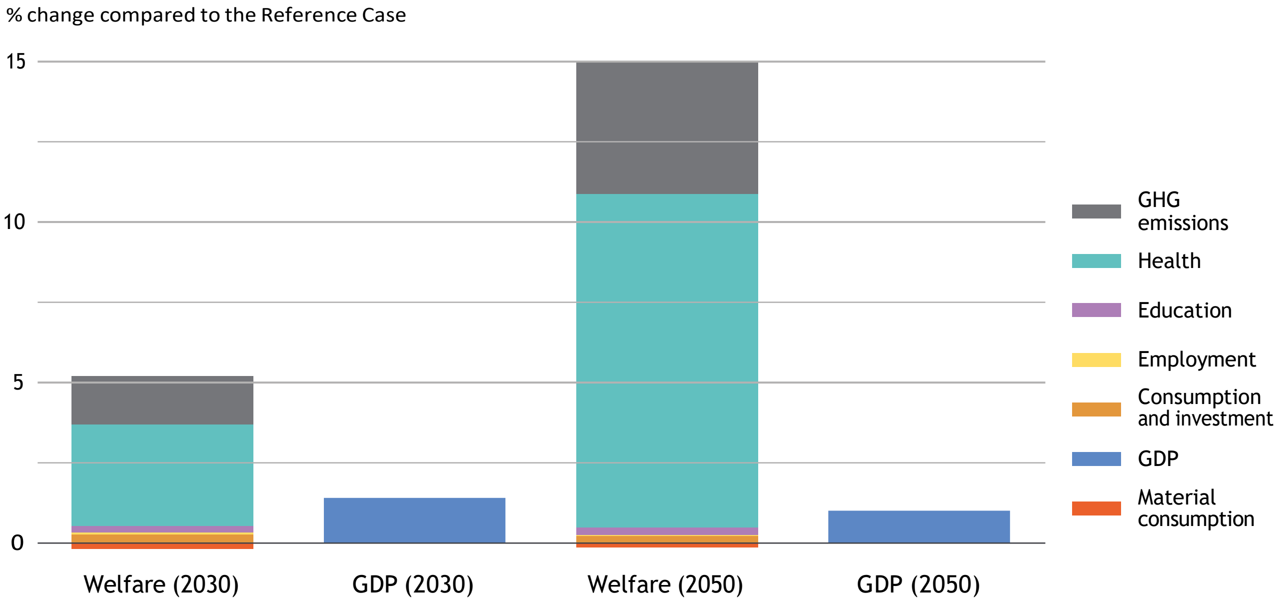
Global welfare in 2050 in the REmap Case increases by 15%, compared to a 0.9% rise in GDP (both measured against the Reference case). This is mainly because of the important reduction in negative health effects from local air pollution (- 62%) and because of the reductions in greenhouse gas emissions (-25%, in cumulative terms).

By 2030, global welfare improves 5%, a significantly lower value than the 15% in 2050. This is because social and environmental improvements (mainly thanks to reductions in health impacts and greenhouse gas emissions) become more relevant in the longer term, where the change in the global energy system becomes much deeper.

Therefore, we can see how the difference between welfare and GDP improvements increases with time. The GDP improvement is a dynamic response to the initial investment stimulus which for the REmap roadmap reaches a peak and then declines within the period up to 2050. On the other hand, some of the welfare dimensions take more time until they reach their maximum benefit (local pollution), and other welfare dimensions (GHG emissions) keep on continuously improving throughout time as the benefits accumulate year after year.

Figure 25. The energy transition generates significant increases in global welfare

Welfare indicators and GDP - the REmap Case compared to the Reference Case, 2030-2050, global (%)



Importantly, all countries and regions see improvements in welfare, even the ones that experience GDP reductions (relative to the reference scenario). This sends a clear message to policymakers: even if GDP improvements in some regions may be slightly lower than in the Reference Case as a consequence of the energy transition, the health and environmental benefits are of such magnitude that welfare is positive in all regions.

Under the REmap Case, the **social dimension** improves 32% globally by 2050. The single most important welfare benefit of the energy transition is the reduced harm to health from air pollution. Energy use in cities is much more efficient and clean. Education expenditure is included in the analysis to represent the wider impacts of the energy transition on human capital (Lange *et al.*, 2018). Impacts on this sub-indicator are of the same order of magnitude as GDP impacts (a few percentage points at most). The analysis here, however, has limitations in reflecting the long-term economic benefits of improved education that could be driven by achieving the Sustainable Development Goals, in particular that of energy access.

The **environmental dimension** contributes a 12% improvement in welfare, through greenhouse gas emissions (25% improvement) and materials consumption (which, interestingly shows a negative impact of 0.8%). Global cumulative (2018-2050) greenhouse gas emissions are substantially lower (25%) in the REmap Case (a global 44% reduction in 2050). The largest reductions take place in India and South Africa, followed by the rest of East Asia and Oceania. Materials consumption (excluding fossil fuels) increases in the REmap Case, since the improvement in GDP over the reference scenario is driven by increased consumption, worsening the materials consumption sub-indicator.

Lastly, the **economic dimension** (0.7% improvement) is evaluated in terms of consumption plus investment (1.2%) and employment (0.1%). Consumption is often used alone as a welfare measure. However, this ignores improvements in capital that contribute to future consumption, so the sub-indicator adds both household consumption and economy-wide investment (*i.e.*, capital formation). Total employment was also discussed in the previous sections.

REGIONAL GDP, EMPLOYMENT, WELFARE

In absolute terms all regions experience GDP growth. However, the socio-economic benefits of the energy transition are not evenly distributed. This is because the various drivers play out differently across countries and regions, depending upon their energy systems, ambition of the energy transition, and socio-economic characteristics.

Figure 26, Figure 27 and Figure 28 present the change in GDP, employment and welfare of the REmap transition over the Reference Case in 2050 for different regions, countries and groups of countries.

It is important to emphasise that all countries and regions see improvements of welfare, even those that experience less growth of GDP than they would under the reference scenario (Figure 26 and Figure 27). Furthermore, across all regions welfare improvements are significantly higher than GDP gains, reflecting the high positive impact of the transition on the social and environmental welfare dimensions, which the GDP does not manage to capture. Yet certain transition challenges need to be addressed to ensure that all regions benefit from the energy transition (see Box 3).

Figure 26. Impact of the energy transition on GDP

GDP impacts in select regions & countries - the REmap Case compared to the Reference Case, 2050 (%)

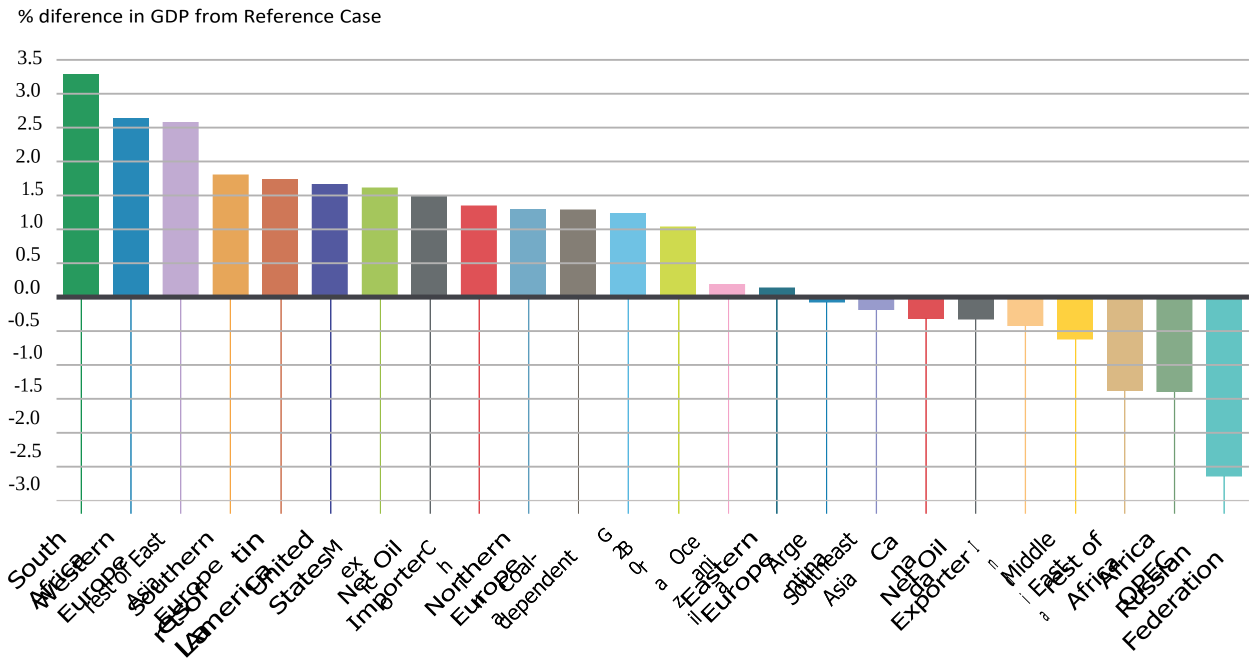


Figure 27. Impact of the energy transition on welfare

Welfare impacts in select regions & countries - the REmap Case compared to the Reference Case, 2050 (%)

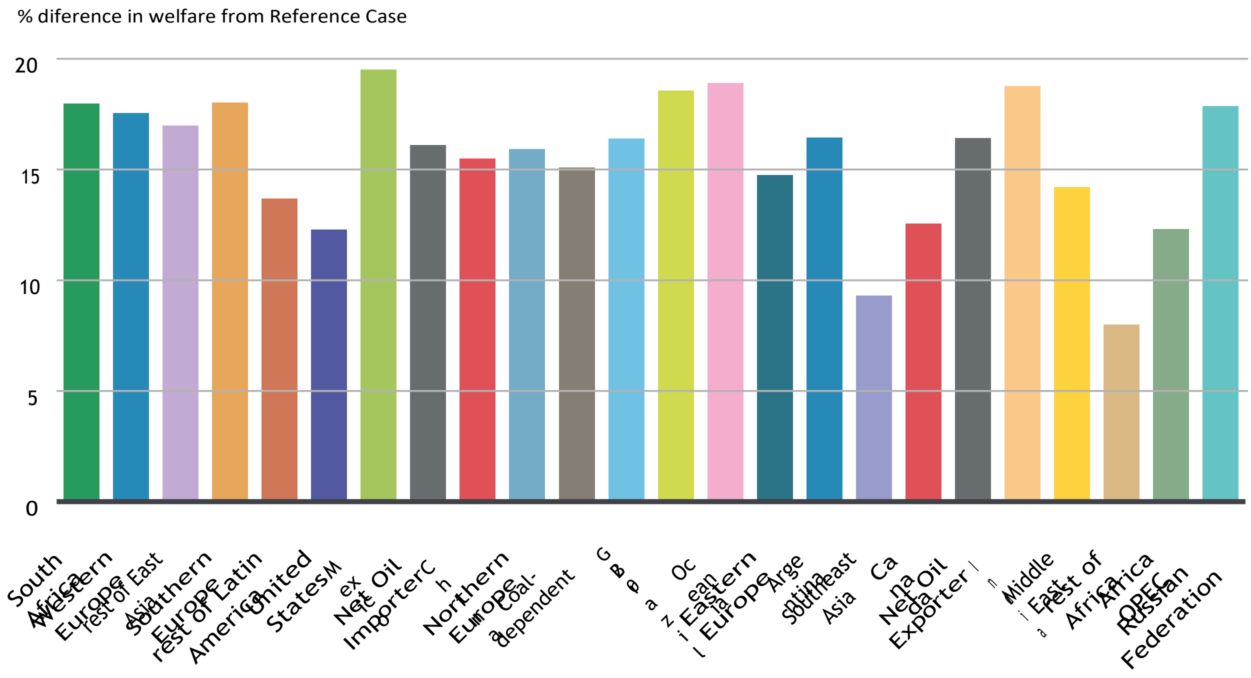
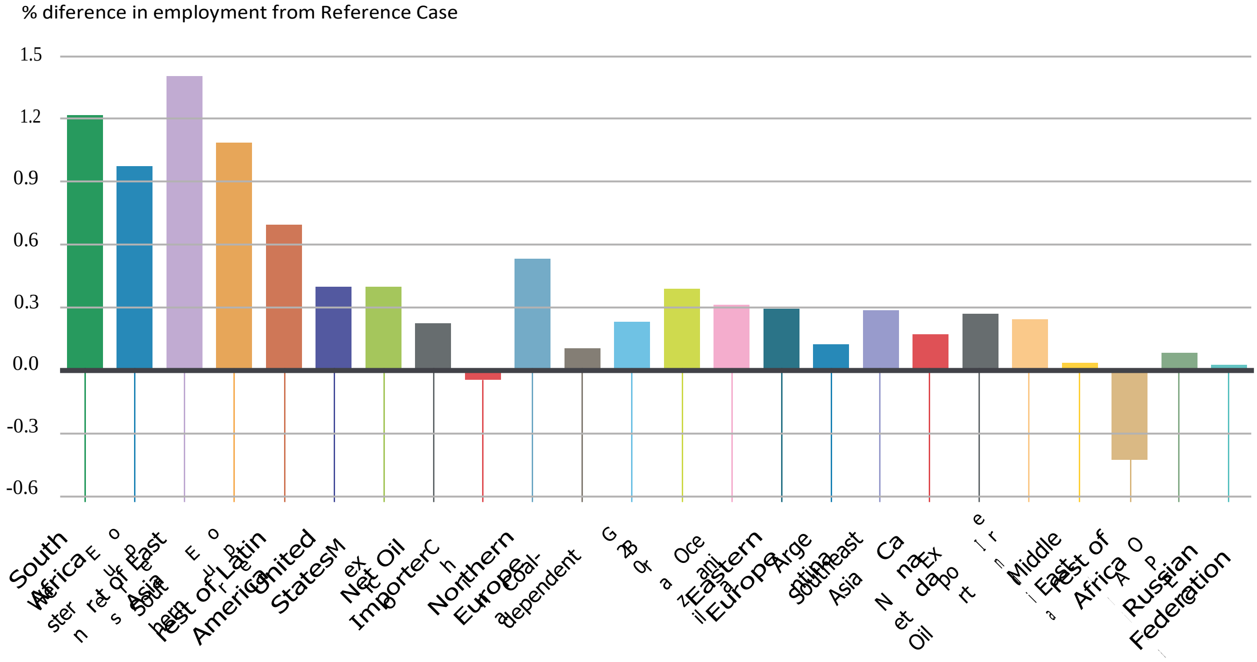


Figure 28. Impact of the energy transition on employment

Employment impacts in select regions & countries - the REmap Case compared to the Reference Case, 2050 (%)



As is the case for the world economy as a whole, the GDP, employment and welfare results across different regions are shaped by the key drivers. Some key findings are discussed below.

GDP

While the energy transition increases global GDP by 2050 by about 1% (relative to the Reference Case), many economies will fare better and some worse. In general terms, the GDP of countries that depend on fossil fuel revenues could experience a hit as demand decreases, in particular, the Middle-East, the rest of Africa, Africa OPEC and the Russian Federation (see Box 3). The effects in specific regions of some of the main macroeconomic drivers are discussed below.

- **Investment.** Investment plays a key role in many countries and regions, and in most cases has a positive impact. Under the REmap Case, increased investment raises the GDP of most countries and regions. The positive effect peaks around 2030, after which it gradually declines until 2050. Investment particularly benefits the rest of Latin America and Middle East regions. Brazil is projected to face the biggest loss in GDP growth because it will experience high foregone investment in the rest of the economy (mainly upstream fossil fuel supply and crowding out). Oceania, Net Oil Exporters and the Russian Federation also face marginally negative effects of investment.
- **Trade.** Trade causes small positive impacts in many regions and negative impacts in a few. It has a marginally positive role in the G20, oil importing countries, coal dependent countries, and Southeast Asia. Countries such as Brazil and South Africa experience a positive impact in both 2030 and 2050 due to a sharp decrease in imports of fossil fuel and an increase in consumption of domestic goods and services. The rest of Latin America region is negatively influenced by trade throughout the transition period, primarily due to shifts in prices and increased imports of consumer goods and services.
- **Tax rate.** Changes in tax rates have a negative impact only in Africa OPEC, India and Southeast Asia, in both short (2030) and long term (2050). In Africa OPEC and Southeast Asia this is mainlydriven by the fall in fossil fuel revenues (which increases income tax for consumers). The caseof India is different. There, the negative impact arises because the government benefits fromthe phase-out of fossil fuel subsidies more in the Reference Case than the Transition Case. The Middle-East and Oceania enjoy the biggest benefits from changes in the tax rate driver because they save more on energy subsidies in these regions.
- **Indirect and induced effects.** In the long run, indirect and induced effects play the biggest role in driving GDP growth in many regions of the world. This effect is stronger in regions and countries that redirect their consumption to the domestic supply chain during the energy transition. South Africa enjoys the biggest benefit from this driver partly for this reason, and partly because inflation falls. Given existing economic structures, the Middle East, Rest of Africa, the Russian Federation and to a lesser extent Africa OPEC are particularly affected by the impact of this driver on GDP.

WELFARE

The greatest overall improvement in welfare (19% or more) is found in Mexico, followed by Brazil, India and Oceania. These are countries and regions in which the impact of pollution on health falls sharply. The transition also generates high welfare improvements in other regions/countries, including the rest of East Asia, South Africa, Southern Europe and Western Europe. Even regions that derive smaller welfare improvements gain significantly (above 8%). All countries gain similar levels of environmental benefit because this dimension is dominated by reduced GHG emissions, for which a single global value was used.

EMPLOYMENT

Under the REmap Case, the regional net gain in employment (relative to the Reference Case) fluctuates over time. Even so, the energy transition has a positive impact on almost all regions and countries. Some developing countries, mostly located in Africa (and in parts of Asia) experience negative impacts because the benefits of transition are not distributed fairly within the socio-economic structure. Reforms are required to correct this effect. Some of the main employment impacts in specific regions are discussed below.

- **Investment.** Although investment kickstarts the employment benefits generated by the transition, over the whole period it plays a less significant role in many regions and countries than other drivers. Southeast Asia and South Africa benefit the most from increased investment in the long term, while by 2050 investment is a significant drag on employment in India.
- **Trade.** Turkey and India experience relatively significant positive trade impacts by 2050. Most regions, however, face impacts that are either relatively small or negative. Southeast Asia and the Rest of Africa regions face the most adverse impacts in 2050. In Southeast Asia, this is due to the negative impact of changes in non-energy trade; changes in fossil fuels trade have a marginal impact. In Indonesia, however, trade causes only a slight negative drag on employment by 2050, because the fossil fuels trade has a strong negative impact but this is balanced by the significant positive impact of non-energy trade. For the rest of Africa, trade in fuels produces a strong negative impact that the region only partially attenuates by marginally improving non-energy trade.
- **Consumer expenditure.** Brazil, the rest of East Asia, all of Europe and South Africa benefit the most from consumer expenditure. All these regions and countries have in common a consumer-focused economy with strong supply chains in the local economy. On the other hand, consumer expenditure negatively affects African OPEC members and countries in the rest of Africa grouping. This is again because they lose revenues and employment in the fossil fuel sector and increasingly rely on imports because local supply chains are weaker. In the rest of Africa, there is a very significant positive spike in consumer expenditure in the first half of the transition, associated with the creation of new jobs and significant additional investment. This suggests that an ambitious energy transition would increase benefits to the region, but also that the absence of adequate and stable policies would reverse this dynamic. In this case, consumer expenditure would inhibit job creation.

Box 3 Addressing fossil fuel export dependency and other transition challenges

Figure 26 clearly shows that in GDP terms the REmap transition roadmap has some countries and regions emerge as winners, relative to the Reference Case, while others are losers. However, this is not an unavoidable outcome of the transition, but rather the consequence of imperfections in the transition path and/or socio-economic system. **The outcome can be improved by addressing the underlying structural dimensions.**

Dependency of an economy from fossil fuel exports is one of the main structural elements leading to a deterioration of GDP relative to the Reference Case, because the transition entails a reduction in fossil fuels demand and hence a reduction of the exports from these economies. The position of each country in the fossil fuel supply-cost curve determines how strong this negative impact will be. This contributes to explain the relatively poor performance of rest of Africa, since many of the countries within this region are oil exporters positioned in the high end of the supply-cost curve. The entailment of the domestic supply chains with the fossil fuel industry also contributes to determine the final impact from this element, which contributes to explain the poor GDP performance in the Russian Federation. Addressing this structural element requires anticipating to the situation forecasted by the macroeconomic model by actively diversifying the economy and reducing its dependency from fossil fuel exports. In many cases, this involves addressing regional just transition considerations, since big parts of the society from these countries is currently held hostage by the fossil fuel industry that has benefited the growth of the economy elsewhere.

A low regional ambition of the transition is another structural element that can lead to an underperformance relative to the Reference Case. In the rest of Africa, the relatively low transition investments are soon offset by the foregone fossil fuel investments, dragging the economy. The investment stimulus associated to increasing the transition ambition beyond past trendsin low-income countries, would lead to GDP and employment increases over the Reference Case, facilitating that these countries participate from the benefits of the transition. Moreover, comparatively increasing the transition ambition in low-income countries is closely related to fair transition considerations, since these countries have the lowest historic responsibility on the current climate crisis because of using a fraction of the historic carbon budget well below their fair share.

Weak domestic supply chains also contribute to the underperformance relative to the Reference Case, which is another of the drivers of the poor transition performance obtained for rest of Africa. In the absence of strong and deep domestic supply chains an economy cannot reap all the benefits from the energy transition investment stimulus, with other countries benefiting from its direct and indirect effects. Moreover, in the absence of deep domestic supply chains, an economy does not benefit from the induced effects driving the GDP and employment improvements in the long term, experiencing negative trade impacts by seeing its import dependency increase even in non-energy products.

A priority investment programme, funded by international climate finance, addressed to increase the transition ambition and reinforce domestic supply chains in low-income countries would contribute to overcome these structural barriers.

HOW FINANCE AFFECTS THE ENERGY TRANSITION

Finance is a cornerstone of the energy transition. To achieve the transition, investment must increase significantly beyond the level expected under current and planned policies. The investment trend in renewables has been positive: it increased eightfold between 2004 and 2017, when it was valued at USD 280 billion (Frankfurt School-UNEP Centre and BNEF, 2018). Significant additional growth is nevertheless needed. In 2016, about three quarters of all the investment in renewable energy occurred in China, Western Europe and OECD America, and about 90% of that investment came from private sources in those countries (IRENA & CPI, 2018). In other regions, public finance accounted for a much larger proportion of direct renewable energy investment: 41% in Sub-Saharan Africa, 49% in Latin America and the Caribbean, and 24% in South Asia.

The lack of effective transition until now is likely to lead to significant investment requirements for climate change adaption, and further delays will decrease the available time window for deployment of capital within a specific climate goal, increasing the required investment rate, which in turn introduces additional pressures in the financing system. In this analysis, two elements associated with potential investment restrictions (cost of capital and crowding out) have been assessed, and their quantitative impacts on the transition's socioeconomic footprint have been estimated.

First is the cost of capital and its link to higher levels of debt. The cost of capital varies across projects, industries and countries, and is based on many factors which ultimately boil down to the level of risk that lenders perceive. One risk factor is the indebtedness of the stakeholders that implement the energy transition, with the assumption that such indebtedness would grow in a context of increasing financing requirements. Despite the effect of higher debt ratios on the cost of capital, and its associated impact on final energy prices, the REmap Case still generates more benefits than the Reference Case. In addition, the analysis found that more expensive capital has a relatively marginal impact, though it lowers increases in both GDP and employment. The negative effect of more expensive capital also increases over time; it is modest until 2030 but becomes substantial by 2050.

With rising levels of ambition, higher cost of capital could have significant impacts on the transition unless appropriate polices are put in place to address this issue. Moreover, those countries and regions which already face high borrowing costs due to certain country-specific risks may face an even greater challenge. Finally, since currently available information on the cost of capital to finance the transition is very scarce, close monitoring is needed so that policymakers can anticipate emerging barriers.

The second element is the crowding out of capital due to additional investment requirements. This will occur, for example, if the additional capital needed to finance the energy transition is taken from other sectors of the economy. The report's macroeconomic analysis assumes that 50% of net additional investment is crowded out from other sectors. Since this effect is subject to high uncertainty, the goal was to identify the factors that drive crowding out and evaluate how they and any crowding out they cause can be distributed throughout the world economy during the energy transition.

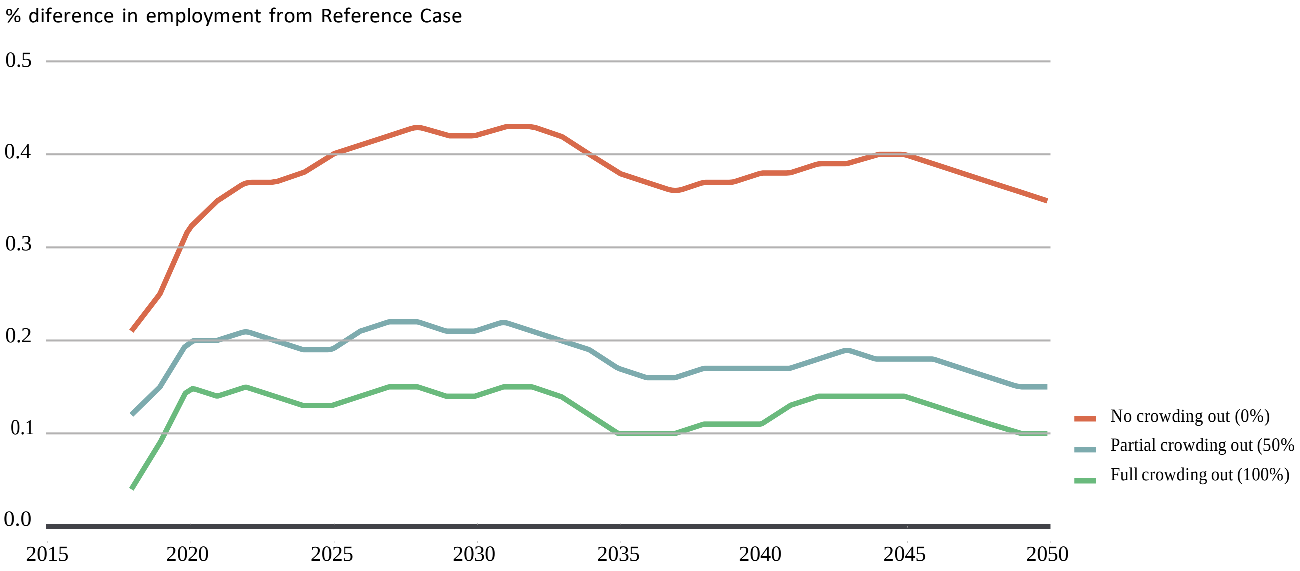
Empirical evidence supports the post-Keynesian view of money supply which posits that commercial banks (rather than the central bank) create money, within macroeconomic conditions and reserve requirements, whenever they hand out new loans and create matching deposits (Campiglio, 2016; Pollitt and Mercure, 2018). Within this framework, there is no crowding out of investment in one sector as a result of higher investment in another sector. However, there are differences between countries in the extent to which money can be created, because policymakers use a variety of tools and in varying degrees to foster financial and economic stability. While in many developed countries, the mandate of central banks is fairly limited to maintaining price stability (inflation targeting) by setting the base rate (interest rate at which central bank lends money to commercial banks), in the emerging and developing countries, central banks and other financial authorities exhibit a higher degree of control on the dynamics of credit growth, as they deploy a wider range of policy tools, such as reserve requirements and macroprudential policies, to safeguard financial stability in addition to price stability (based on review of Akinci and Olmstead-Rumsey, 2018; Campiglio, 2016; Cerutti *et al.*, 2017; Zhang and Zoli, 2014).

As well, there is a clear difference between banks and non-bank private investors, as the non-bank private investors largely operate by reallocating the existing stock of credit, whereascommercial banks can also allocate new money, and thus create new money (Campiglio, 2016). This element also points to a potentially higher risk of crowding out in those regions which are less reliant on private sector capital (and therefore more reliant on public sources of capital) to finance the energy transition. As mentioned earlier, less developed countries are currently more reliant on public finance to finance renewable power compared to more advanced economies. Therefore,although the currently assumed 50% crowding out is highly likely a very conservative assumption for the global economy in the current context, important regional variations of crowding out should be expected, with a higher crowding out in poorer regions, contributing to an increasing inequality along the energy transition.

To quantify the macroeconomic impact of crowding out, a sensitivity analysis tested two extreme cases, of 0% and 100% crowding out. In the first extreme case (100% crowded out), the REmap Case generates better GDP and employment outcomes than the Reference Case, but there is a very significant impact on both (the employment impacts are shown in Figure 29). In the opposite scenario (no crowding out), changes in both GDP and employment are about twice as high in most years than under a midway scenario (50% crowding out). Changes of GDP and employment are lower under the 100% scenario than they are under the 50% scenario, but the deterioration is relatively less pronounced than under the 0% relative to 50% scenario.

Figure 29. Crowding out of capital does affect employment, but the energy transition still generates positive employment growth

Relative increment of employment for different crowding-out assumptions - the REmap Case relative to the Reference Case, global (%)

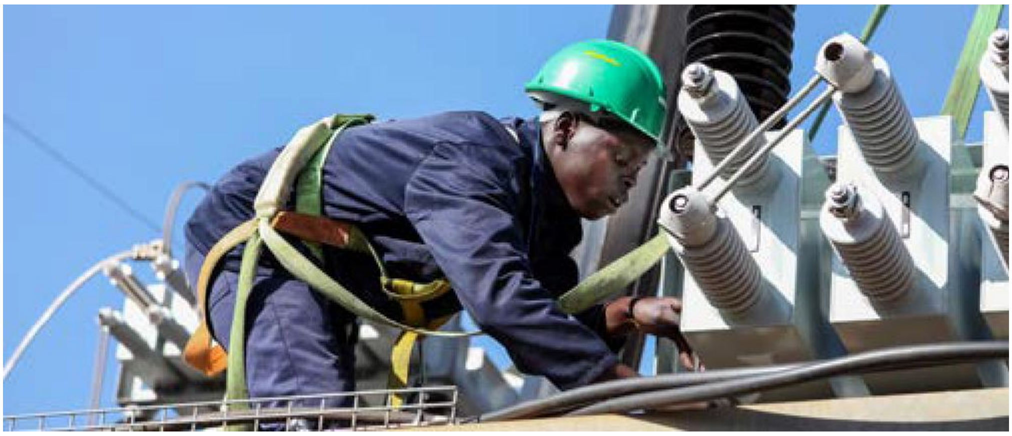


Policy measures and structural socioeconomic modifications can limit the extent of crowding out without compromising financial stability. Realigning economic flows during the transition (for example, by means of carbon taxes and phasing out fossil fuels subsidies) can generate new sources of capital. Unlocking new sources of capital, for example from institutional investors or socially driven and community-based finance, can help reduce crowding out effects in the economy. Finally, even where crowding out occurs, policies and regulations can direct the crowding out effect to make sure that it does not hurt socially sensitive sectors.

KEY SOCIO-ECONOMIC MESSAGES

Understanding the socioeconomic footprint from the energy transition is fundamental:

- **The energy transition** cannot be considered in isolation from the associated **socio-economic system**. The interactions between both determine the overall transition outcome. Favouring the synergies between them offers the potential to maximise the benefits from the transition.
- While this analysis has focused on a particular scenario, transition pathways may vary, as does the transformation of the socio-economic system itself. Irrespective of the particular path chosen by policymakers, the **socioeconomic footprint** of the overall transition provides an adequate means to measure its performance.
- The REmap energy transition **significantly improves the global socioeconomic footprint** overthe reference scenario, providing in year 2050 global increases of 15% in welfare, 1% in GDP and0.1% in employment.
- The socioeconomic benefits from the transition (**welfare**) go well beyond GDP improvements, and are strongly dominated by social and environmental benefits (reduction of local air pollution and reduced climate impacts due to reduced GHG emissions)
- At **regional level** the outcome of the REmap energy transition depends on the combination of its regional ambition and the regional socioeconomic structure. Significantly **different regional socioeconomic footprints** are obtained from the REmap energy transition, with clear winners and losers, and increasing inequalities that could eventually develop in transition barriers.
- Regions with socioeconomic systems dependent of oil exports or weak socioeconomic structures, can see GDP and employment reductions relative to the Reference Case, though still they will experiment a significant welfare improvement.
- The capability of a region to reap the long lasting indirect and induced transition benefits depends on how much its domestic supply chains contribute to the energy transition deployment and to the induced economic activity.
- Maximising the socioeconomic benefits of the energy transition requires increasing the transition ambition, internalising climate externalities (carbon taxes, fossil fuel subsidies phase-out), and stimulating the diversification and reinforcement of deep domestic supply chains.



The energy sector benefits from the energy transition but holistic employment policy is required:

- Within the energy sector, **more jobs are created by the transition than those lost in the fossil fuel industry**. The REmap energy transition would lead to a loss of 7.4 million jobs in fossil fuels by 2050, while a total of 19.0 million new jobs could be created in renewable energy, energy efficiency, and grid enhancement. The net change is a gain of 11.6 million jobs.
- The global **renewable energy workforce could rise** from just 9.8 million in 2016 to around 23.7 million in 2030 and 28.8 million in 2050 following an accelerated ramp up in deployment of renewables in line with the REmap roadmap.
- To meet the human resource requirements of a rapidly expanding renewable energy and energy efficiency sectors, **education and training policies** would need to consider and plan for the skills needs of these sectors, minimising the import of foreign labour and maximising local value creation.
- The **geographic distribution of energy sector jobs** gained and lost are unlikely to be aligned. This could introduce challenges for maintaining employment among fossil fuel workers if thefocus is only put on retraining within the energy sector. Induced and indirect jobs created by the transition in other parts of the economy dominate the transition employment creation (especially with low crowding out) and are more homogenously distributed than direct energy-related jobs. Additional measures such as social protection programmes and adequate transition support are critical.

Improving the transition's socioeconomic footprint:

- Modifying the socioeconomic structure incorporating fair and just transition elements improves the socioeconomic footprint and prevents barriers that could ultimately halt the transition. The transition of the socioeconomic system itself offers a high potential for maximising the benefits from the overall transition.
- The socioeconomic footprint can be substantially improved by increasing the energy transition ambition in alignment with the climate requirements and by addressing regional issues, aiming at a 100% RES share before 2050, in line with the available carbon budget to limit warming within 1.5°C.
- Negative impacts on low-income countries must be addressed for the transition to be successful. Increasing the energy transition ambition and prioritising climate finance to steer the transition in these countries, reinforcing domestic supply chains to reap indirect and induced effects from the transition, and redirecting global economic flows with fairness criteria (*i.e.* regional redistribution of carbon tax incomes), can all contribute to address these issues.

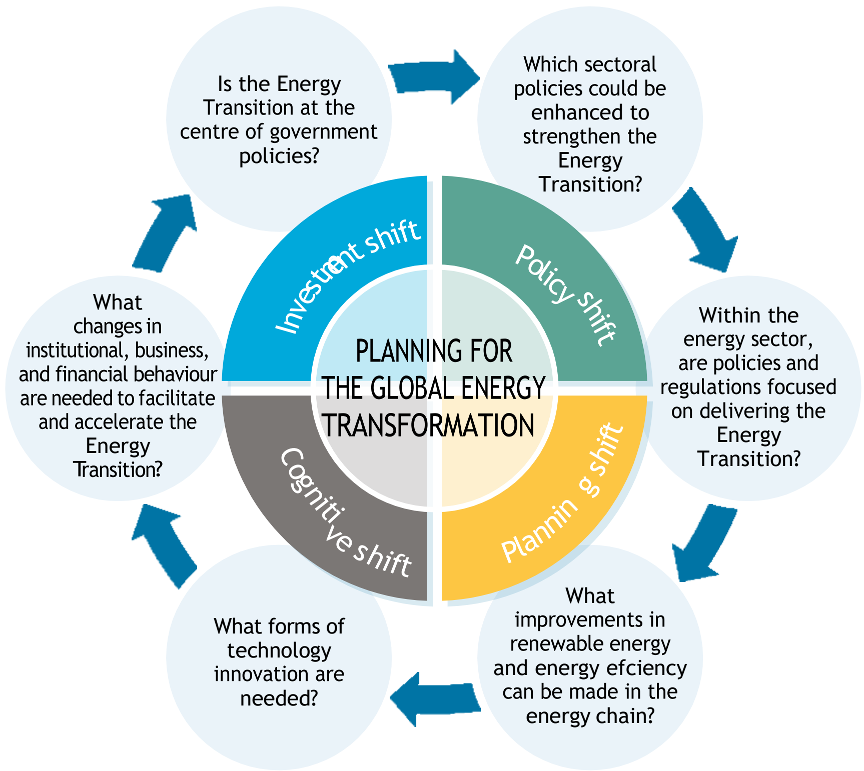
The role of finance as a transition cornerstone:

- **Financial constraints** can act as brakes to the mobilisation of finance required to deliver the energy transition – furthermore, their impact can be expected to increase over time and they may affect the already disadvantaged regions especially harshly.
- **Act fast.** Climate boundaries require a fast scale-up of investment in renewable energy and energy efficiency in a relatively short time window. As well, the further we delay the scale-up in investment, the higher will be the cost of capital needed to finance the transition. Therefore, fast action is needed to lower this potentially significant transition barrier and to ensure that the benefits of moving towards cleaner and more modern energy sources are no longer delayed.
- The financial system should be aligned with **broader sustainability and energy transition requirements**.
- **Crowding out** has an important impact in the GDP and employment improvements over the Reference Case: reducing crowding out from 50% to 0% produces an improvement of 60% in GDP and of 100% in employment. Although the assumed 50% crowding out seems a very conservative assumption for the global economy in the current context, important regional variations of crowding out should currently be expected, with the higher crowding out in poorer regions, contributing to the increasing inequality along the energy transition.
- **Policy measures and structural socioeconomic modifications** could limit the amount of effective crowding out, even without compromising regional financial stability. One example would be realigning transition economic flows (carbon taxes, fossil fuels subsidies phase-out) with regional redistribution criteria addressing fair transition issues. Even in the presence of crowding out, adequate policies and regulations can properly direct the crowding out effect making sure that it does not bite from socially sensitive sectors.
- **Underutilised sources of finance should be unlocked**. One potential source are **institutional investors** (pension funds, insurance companies, endowments and sovereign wealth funds), who managed about USD 96 trillion in total assets in 2013 in OECD, yet provided less than 1% of the primary financing of renewable energy in the 2013-2016 period.
- Another source of capital that should be fostered is **community-based finance.** This has a broader range of considerations compared to 'traditional' investors, and can help lowering the overall cost of borrowing for the transition and reduce the risk of undesirable crowding-out, while simultaneously facilitating the involvement of society in the transition.

HOW TO FOSTER THE GLOBAL ENERGY TRANSFORMATION: **KEY FOCUS AREAS**

The challenge that policy makers around the world face is how to accelerate the transition. Fully delivering the energy transition will require a transformation in how we view and manage the energy system. Transitioning in a few decades from a global fossil-fuel powered energy system, built-up over several hundred years, to one that is sustainable, will require a much greater transformation than current and planned policies (the Reference Case) envisage.

Figure 30. Planning for the global energy transformation



Planning for the energy transition requires fundamental shifts in policies, investments, planning processes, attitudes and behaviour.

Not only governments should take the lead. To stimulate the innovation process, and shape and create technologies as well as sectors and markets, new relationships and closer partnerships must be developed with the private sector. Coordination of the efforts of this network with stakeholders is vital, using the state's convening power to build trust and targeted policy instruments to achieve clear goals. Delivering innovation will require national governments, international actors and the private sector to act in an intensive, focused and more co-ordinated manner. Action is urgently required because a full-scale energy transition will take decades to implement due to the different technologies that must be developed and the long lifespan of existing capital stock.

Facilitating and encouraging behaviour change with respect to energy consumption and the supply of energy services is a critical element of an accelerated energy transition. Together with digitalisation, education and regulation help to encourage and support changes in behaviour. These might encourage the local generation of renewable energy, the adoption of energy efficiency improvements, recycling and reuse, etc. Businesses will be required to innovate and adapt to a decarbonised global energy matrix. Utilities will need to review their business models. All stakeholders will need new management and governance skills to enhance transparency, accountability and enforcement of clean energy policies. Incentive schemes must be designed to permit consumers to become net clean energy producers.

The following section sets out some key priorities and practical policy measures that will help policymakers accelerate the energy transition.

FOCUS AREA 1. TAP INTO THE STRONG SYNERGIES BETWEEN **ENERGY EFFICIENCY AND RENEWABLE ENERGY**.

To achieve this objective, government policymakers should:

- Combine energy efficiency and renewable energy measures (for example, public sector policies that integrate renewable technologies in the renovation of public buildings).
- Deploy technologies that promote renewable energy and increase energy efficiency (for example, combined heat and power (CHP) systems fuelled by renewables to recover waste heat for use by industrial plants or commercial and residential buildings).

FOCUS AREA 2. PLAN A **POWER SECTOR** FOR WHICH **RENEWABLES PROVIDE A HIGH SHARE** OF THE ENERGY

Power systems are changing at a pace that has not been seen since the start of the electric utility industry over a hundred years ago. Several interconnected policy and operational changes will need to occur to enable power systems to make extensive use of renewable energy, particularly sources of variable renewable energy such as photovoltaic solar and wind power. To achieve this objective, policymakers should:

- Support investment to enable infrastructure to integrate VRE and smart technologies (including batteries, smart charging for electric vehicles, blockchain, machine learning, use of "big data") that have the potential to optimise extensive use of renewables to generate power.
- Promote time-responsive power-to-heat, power-to-cool, power-to-hydrogen systems that heat, cool or produce energy at off-peak or low-price periods or can absorb excess renewable electricity.
- Promote innovative business models that enhance the system's flexibility and incentivise deployment of renewable technologies. Examples include virtual power plants, innovative forms of power purchase agreements, platform business models such as peer-to-peer trading, and business models that enhance demand side response.

FOCUS AREA 3. **INCREASE USE OF ELECTRICITY** IN **TRANSPORT, BUILDINGS AND INDUSTRY**

This will help to unlock substantial efficiency gains and yield a wide range of other benefits, including the reduction of air pollution in cities. To achieve this objective, policymakers should:

- Set targets for the replacement of conventional fossil fuel-based technologies by electric vehicles, heat pump systems, and electrical stoves.
- Facilitate sector coupling between power and end-use sectors, to facilitate the integration of variable renewables in the power sector.
- Increase flexible electricity demand by means of demand side management, smart charging and vehicle-to-grid for electric vehicles, flexible heat pump heating and cooling, thermal storage fed by electricity, etc.
- Use information communication technology and digitalisation, along with demand side management, to reduce peak electricity demand, lower the need to invest in power capacity, and reduce operational costs.

FOCUS AREA 4. FOSTER SYSTEM-WIDE **INNOVATION**

Innovation has played a key enabling role in energy transition to date, particularly in solar and wind technologies. A critical but often underappreciated point is that innovation is far broader than technology research and development: it must cover a technology's life cycle, including demonstration, deployment (technology learning) and commercialisation. Innovation ecosystems should also cover a wide range of activities, including new approaches to power system operation, market design, enabling technologies, and business models. Alongside innovative generation technologies, innovation is needed across the whole energy system to assist the system to integrate variable renewable energy generation and accelerate the widespread adoption and scale-up of clean energy.

To accelerate the energy transition Governments should:

- Support the formation of an Energy Transition Coalition that will bring together countries that lead the development of long-term energy transition strategies, foster investments in low carbon energy, and increase investor confidence in low carbon economic growth.
- Increase public sector investment in research, development and demonstration (RD&D), aligning with pledges made by Mission Innovation members at the Paris Climate Agreement (COP21).
- Co-operate with and strengthen international programmes (such as IRENA, the IEA, and its Technology Collaboration Programmes and Mission Innovation) to define a joint agenda for renewable technology innovation that will identify the critical innovation needs of developed, emerging and developing markets and prepare collaborative strategies to meet them.
- Improve global understanding among key public and private sector actors of critical innovation needs.
- Establish more bilateral and multilateral demonstration projects, at commercial scale and funded publicly or privately, as well as "real-world" pilot programmes to test innovative technologies and processes.
- Encourage the development of internationally harmonised technical standards and quality control standards to facilitate cross-border trade and exchange of innovative technologies.
- Concentrate RD&D efforts to assist sectors that lack commercially available decarbonisation solutions. Relevant sectors include energy intensive industries (iron, steel and cement production) and transport (freight, aviation and shipping).

FOCUS AREA 5. **ALIGN SOCIO-ECONOMIC STRUCTURES AND INVESTMENT** WITH THE TRANSITION

The success of the energy transition depends on how well it is connected to efforts to address the transition of the broader socio-economic system itself. Implementing the energy transition requires significant investments. More than that, climate boundaries require a rapid scale-up of investment in renewable energy and energy efficiency within a relatively short time window. The quicker that the energy transition gets under way, the lower the climate change adaptation costs will be and the smaller the socio-economic disruption. But the longer the needed scale-up in investment is delayed, the higher the cost of capital needed to finance the transition. The financial system needs to be aligned with broader sustainability and energy transition requirements. A timely mobilisation of investments requires addressing the barriers that conventional financing faces, as well as mobilising additional investment streams.

- One potential source are institutional investors (pension funds, insurance companies, endowments and sovereign wealth funds). Another is the growth of new capital market instruments, such as green bonds, through which investors can more easily invest in the energy transition. In addition, community-based finance can help lower the overall cost of borrowing for the transition, while simultaneously facilitating the involvement of society in the transition.
- Creating stable and predictable regulatory frameworks and market conditions for investment in clean energy is a key measure to facilitate the reallocation of capital toward low-carbon solutions and to minimise the spectre of stranded assets and avoid long-term lock-in into a carbon intensive energy system.
- While public investment has a role to play, public finance should also be used to help mitigate key risks and to lower the cost of capital in countries and regions perceived as high risk. This can contribute to correct some of the potentially negative GDP impacts on these countries and regions.
- Reducing crowding out of capital from the assumed rate of 50% to 0% produces an improvement of 60% in GDP and of 100% in employment outcomes. At the global level, the assumed 50% crowding is a very conservative assumption in the current context. But there are important regional variations. Expected higher rates of crowding out in poorer regions could result in increasing inequality during the energy transition.
- Carbon taxes, together with the elimination of fossil fuel subsidies, not only provide important signals to the market in favor of decarbonisation of the economy, but can also generate significant additional revenue flows. These flows could be used to boost investments in renewable energy and energy efficiency, align infrastructure and the general economy better with climate goals, or be deployed in support of a fair transition strategy.

FOCUS AREA 6. ENSURE THAT TRANSITION COSTS AND BENEFITS ARE FAIRLY DISTRIBUTED

Although the energy transition promises significant overall GDP, employment and welfare benefits compared to the Reference Case, this cannot be considered in isolation of the socio-economic system of which it is part and which it reshapes. These interactions determine the transition outcome. Different pathways are possible, dependent on the level of ambition, on how targets are translated into specific policy actions, and on the resulting dynamics and synergies.

However, irrespective of the particular pathway followed, different countries and regions will clearly fare differently during the transition. This is a result of several factors, beginning with diverging levels of ambition among countries. But the outcomes also relate strongly to underlying structural realities and the degree to which governments undertake actions such as implementing carbon tax systems in order to guide economies toward a low-carbon future. The analysis in this report finds that countries as diverse as South Africa, as well as nations in Western Europe and the rest of East Asia, can reap substantial GDP, welfare and employment gains relative to the Reference Case.

On the other hand, economies that strongly depend on fossil fuel exports will face considerable challenges during the transition, especially if adjustment efforts are limited or undertaken with delay. Worldwide, many fossil fuel jobs will be lost, even as a larger number of jobs are created in renewable energy and energy efficiency. In particular, the REmap Case analysis finds that oil exporters in the Middle East, parts of Africa, and the Russian Federation will have less GDP and employment growth in the energy transition than under business as usual.

The capability of a country or region to reap the GDP, employment and welfare benefits of the transition also depends to a large extent on the degree to which domestic supply chains can respond to new economic demand patterns stimulated by the transition. Countries with well-developed industries and service sectors will benefit significantly more than those that depend heavily on imported inputs.

As a result of diverging economic structures, the energy transition will generate uneven outcomes. The REmap analysis focuses on the national and regional levels, but within a given national economy particular areas will also fare better or worse, depending on their socio-economic structure. This cannot be considered solely as a matter of overall employment numbers. The geographic distribution of jobs gained and lost may not be in alignment. Similarly, new job creation may not occur within the same time scale as jobs losses, requiring additional adjustment measures.

It is against this backdrop that the concept of a just and fair transition assumes great importance. Spreading the benefits of the transition widely and limiting any resulting socio-economic difficulties is essential not just as a matter of fundamental fairness, but also to limit the likelihood that those negatively impacted will oppose policies required to render the world's economies climate-safe. A transition can be just if it entails policies to support needed economic restructuring.

A transition can be regarded as fair to the degree that it also seeks to reduce historical divergences in levels of energy access. Universal energy access is in fact a key component of a fair and just transition. Beyond energy access, huge disparities exist in the energy services available in different regions. The transition process will only be complete when energy services converge in all regions.

- Just transition entails a number of policies, and the mix of policies that are needed will vary from country to country. It includes a set of industrial policies that support the creation of domestic supply chains capable of responding to the economic dynamic triggered by the transition. Governments can do so through tools such as providing preferential access to credit, land and buildings, but also through the formation of economic incubators and industry clusters. Public investments can stimulate the diversification of the economy as needed.
- Another critical element concerns education and training policies, including an assessment of the occupational patterns and skill profiles in rising and declining industries, and how workers might most successfully be retrained. Because reskilling and other adjustments take time and are not always certain to succeed, there is also a need to provide interim support, such as unemployment insurance and other social protection measures.
- From the perspective of ensuring a fair transition, adjustment challenges need to be considered beyond urban, industrialised settings, with wider energy access and convergence considerations being factored into energy transition scenarios and planning. In particular, these considerations need to be an explicit part of any socio-economic footprint evaluation of transition roadmaps.
- From the outset, governments need to approach just transition in ways that explain the specific implications at micro and macro levels. A central goal of a just transition policymust be to create structures that enable individuals, communities and regions that have been trapped in a fossil fuel energy system to participate in the benefits of the transition.

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