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International Renewable Energy Agency

GLOBAL RENEWABLES OUTLOOK

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About IRENA

The International Renewable Energy Agency (IRENA) serves as the principal platform for international co-operation, a centre of excellence, a repository of policy, technology, resource and financial knowledge, and a driver of action on the ground to advance the transformation of the global energy system. An intergovernmental organisation established in 2011, IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. **www.irena.org**

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FOREWORD

This first *Global Renewables Outlook* arrives while the world suffers through the COVID-19 pandemic, which brings dramatic numbers of people infected, a mounting death toll, and social and economic disruption for regions, countries and communities.

The priority now remains to save as many lives as possible, bring the health emergency under control and alleviate hardship. At the same time, governments are embarking on the monumental task of devising stimulus and recovery packages. These are at a scale to shape societies and economies for years to come.

This response must align with medium- and long-term priorities. The goals set out in the United Nations 2030 Agenda and the Paris Agreement can serve as a compass to keep us on course during this disorienting period. They can help to ensure that the short-term solutions adopted in the face of COVID-19 are in line with medium- and long-term development and climate objectives.

Stimulus and recovery packages should accelerate the shift to sustainable, decarbonised economies and resilient inclusive societies. The Nationally Determied Contributions (NDCs) to be presented by the end of this year, as required under the Paris Agreement, should be the backbone of the stimulus package.

In this respect, the *Global Renewables Outlook* shows the path to create a sustainable future energy system. It highlights climate-safe investment options until 2050 and the policy framework needed to manage the transition. Building on earlier *Global Energy Transformation* reports, it also grapples with the decarbonisation of challenging industry and transport sectors and presents a perspective on deeper decarbonisation.

Raising regional and country-level ambitions will be crucial to meet interlinked energy and climate objectives. Renewables, efficiency and electrification provide a clear focus for action until mid-century. Several regions are poised to reach 70-80% renewable energy use in this outlook. Electrification of heat and transport would similarly rise across the board.

The nature of this crisis calls for a major state role in the response. This involves defining the strategies and initiating direct interventions for the way out. Expansionary budget policies may be envisaged to support this effort.

Economies need more than a kick-start. They need stable assets, including an inclusive energy system that supports low-carbon development. Otherwise, even with the global slowdown momentarily reducing carbon dioxide (CO_2) emissions, the eventual rebound may restore the long-term trend. Fossil-fuel investments would continue polluting the air, adding to healthcare costs and locking in unsustainable practices.

Although renewable energy technologies may be affected by the pandemic just like other investments, energy market dynamics are unlikely to disrupt investments in renewables. Price volatility undermines the viability of unconventional oil and gas resources, as well as long-term contracts, making the business case for renewables even stronger. One further result would be the ability to reduce or redirect fossil-fuel subsidies towards clean energy without adding to social disruptions.

A renewable energy roadmap

Economic recovery packages must serve to accelerate a just transition. The European Green Deal, to take an existing example, shows how energy investments could align with global climate goals. The time has come to invest trillions, not into fossil fuels, but into sustainable energy infrastructure.

Recovery measures could help to install flexible power grids, efficiency solutions, electric vehicle (EV) charging systems, energy storage, interconnected hydropower, green hydrogen and multiple other clean energy technologies. With the need for energy decarbonisation unchanged, such investments can safeguard against short-sighted decisions and greater accumulation of stranded assets.

COVID-19 does not change the existential path required to decarbonise our societies and meet sustainability goals. By making the energy transition an integral part of the wider recovery, governments can achieve a step change in the pursuit of a healthy, inclusive, prosperous, just and resilient future.

While each country must work with a different resource mix, all of them need a 21st-century energy system. The response must provide more than just a bail-out for existing socio-economic structures.

Now, more than ever, public policies and investment decisions must align with the vision of a sustainable and just future. Making this happen requires a broad policy package – one that tackles energy and climate goals hand in hand with socio-economic challenges at every level. A just transition should leave no one behind.

I hope sincerely that this new publication helps to show the way.

Francesco La Camera

Director-General, IRENA

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REGIONAL FACTSHEETS

- EAST ASIA
- SOUTHEAST ASIA
- REST OF ASIA
- EUROPEAN UNION
- REST OF EUROPE
- LATIN AMERICA AND THE CARIBBEAN
- MIDDLE EAST AND NORTH AFRICA
- NORTH AMERICA
- OCEANIA
- SUB-SAHARAN AFRICA

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THIS REPORT AND ITS FOCUS

The International Renewable Energy Agency (IRENA) has produced a succession of studies aiming to quantify and guide the transformation of the world's energy system. These roadmaps provide an ambitious, yet technically and economically feasible, pathway for deploying low-carbon technologies to create a clean, sustainable energy future.

One of IRENA's initial studies, outlined in a key chapter of *Perspectives for the Energy Transition* (IEA and IRENA, 2017), focused on the technical feasibility and socio-economic benefits of long-term global decarbonisation. The subsequent *Global Energy Transformation: A Roadmap to 2050* (IRENA, 2018a), expanded on the implications of accelerated uptake of renewables and investigated the associated investment needs, examined key transition requirements by sector, and offered further insights into the socio-economic implications.

The second edition of the *Global Energy Transformation* roadmap (IRENA, 2019a) updated IRENA's analysis of key countries and regions and underlined the role of renewables-based electrification as a key enabling solution. The report also offered new findings on the costs, subsidies and investment needs of the transition. IRENA's socio-economic analysis delved into the effects of the global transition in terms of gross domestic product (GDP) and jobs as well as an assessment of potential impacts of climate damages.

This *Global Renewables Outlook* reviews the ongoing energy transformation with closer examination of needs and impacts at the regional level, in both energy and socio-economic terms. Going further than the previous studies, this report also outlines a vision for transformative energy policies as the conduit to the creation of a deeply decarbonised global society. On the innovation and technology side, the study grapples with reducing carbon dioxide (CO_2) emissions in challenging sectors, such as shipping, aviation and heavy industry. Addressing such challenges soon will be crucial to achieve net-zero emissions in the second half of the century.

Chapter 1 provides an overview of IRENA's Renewable Energy Roadmap (REmap) energy transformation analysis, highlighting key technology solutions and a vision for a global energy pathway to 2050. Chapter 2 highlights the global socio-economic implications of the energy transformation using the indicators GDP, employment and welfare. Chapter 3 outlines regional techno-economic transformation pathways to 2050, while Chapter 4 describes regional variations in the socio-economic indicators. Chapter 5 explains how to reduce energy and industrial process-related CO_2 emissions to zero and offers solutions for challenging sectors. Chapter 6 discusses the comprehensive policy package, massive resource mobilisation and enhanced international co-operation needed to accelerate the transformative decarbonisation for a sustainable society and to ensure a just transition. In addition, key data and indicators for 10 regions are provided at the end of the report.

SCENARIOS AND PERSPECTIVES IN THIS OUTLOOK

This outlook report presents several scenarios and their socio-economic outcomes:

The **"Planned Energy Scenario (PES)"** is the primary reference case for this study, providing a perspective on energy system developments based on governments' current energy plans and other planned targets and policies (as of 2019), including Nationally Determined Contributions under the Paris Agreement unless the country has more recent climate and energy targets or plans.

The **"Transforming Energy Scenario (TES)"** describes an ambitious, yet realistic, energy transformation pathway based largely on renewable energy sources and steadily improved energy efficiency (though not limited exclusively to these technologies). This would set the energy system on the path needed to keep the rise in global temperatures to well below 2 degree Celsius (°C) and towards 1.5°C during this century.

The **"Deeper Decarbonisation Perspective (DDP)"** provides views on additional options to further reduce energy-related and industrial process CO_2 emissions beyond the Transforming Energy Scenario. It suggests possibilities for accelerated action in specific areas to reduce energy and process-related CO_2 emissions to zero in 2050-2060.

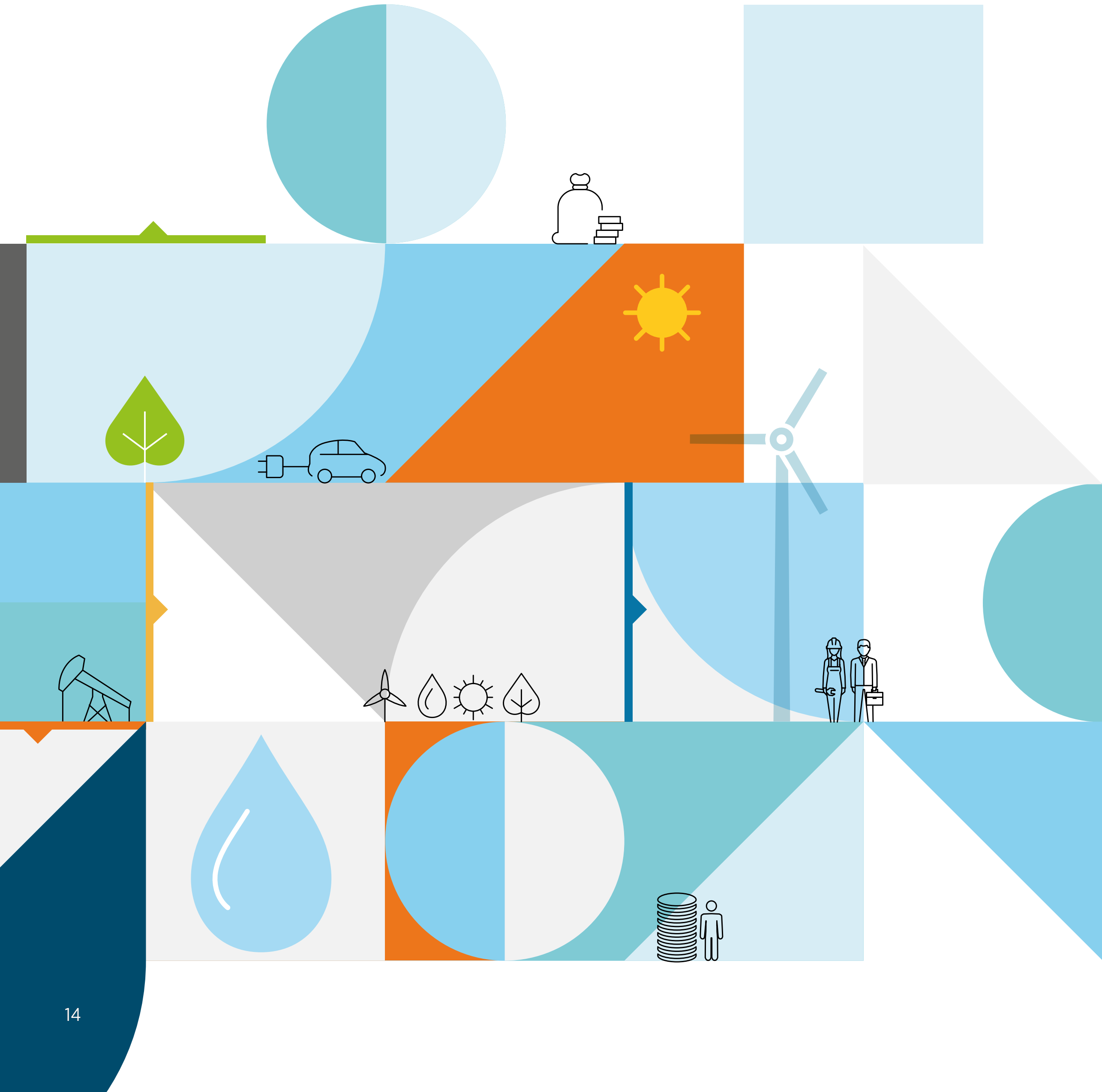
The **"Baseline Energy Scenario (BES)"** reflects policies that were in place around the time of the Paris Agreement in 2015, adding a recent historical view on energy developments where needed.

The **socio-economic analysis** of these scenarios is carried out with a macro-econometric model (via E3ME model) that links the energy system and the world's economies within a single and consistent quantitative framework. It analyses the impact of the energy transition on variables such as GDP, employment and welfare to inform energy system planning, economic policy making, and other measures undertaken to ensure a just and inclusive energy transition at the global, regional and national level.

These various possible paths for energy investment and broader socio-economic development are explored over the crucial three-decade time frame remaining until mid-century. This report considers policy targets and developments until April 2019. Policy changes and targets announced since then are not considered in the present analysis.

The report builds on IRENA's REmap (Renewable Energy Roadmap) approach, which has formed the basis for a succession of global regional, country-level and sector-specific analyses since 2014 as well as IRENA's socio-economic analysis that captures an increasingly comprehensive picture of the impact of the energy transition on economies and societies.

KEY FINDINGS



GLOBAL RENEWABLES OUTLOOK EDITION: 2020

- **The health, humanitarian, social and economic crises set off by the COVID-19 pandemic requires a decisive, large-scale response guided by appropriate social and economic measures.** As countries consider their economic stimulus options, they must still confront the challenge of ensuring sustainability and strengthening resilience while improving people's health and welfare. The need remains for an accelerated path to meet global climate goals through the decarbonisation of our societies.

- **The Transforming Energy Scenario outlined here – coupled with an additional Deeper Decarbonisation Perspective – offers a sustainable, low-carbon climate-safe foundation for stable, long-term economic development.** It promises more jobs, higher economic growth, cleaner living conditions and significantly improved welfare. This ambitious outlook would also cut 70% of the world's energy-related carbon dioxide (CO_2) emissions by 2050. Over 90% of this reduction would be achieved through renewables and energy efficiency measures.

- **The energy transition can drive broad socio-economic development, guided by comprehensive policies to foster the transformative decarbonisation of societies.** This holistic approach would align energy decarbonisation with economic, environmental and social goals. The proposed European Green Deal – including international support for clean energy – provides an example. Economic stimuli after the 2020 health crisis could move many societies in a similar direction.

- **The ultimate global climate goal would be to reach zero emissions.** This outlook also explores ways to cut CO_2 emissions beyond 2050 to net-zero and potentially even zero. Hydrogen and synthetic fuels, direct electrification, advanced biofuels and carbon management will be crucial, along with innovative business models, structural changes and behavioural adaptation.

- **Still, the last portion of the world's CO_2 emissions will be the hardest and most expensive to eliminate.** An ambitious energy transition would still leave global emissions at about one-third of their current levels, with energy-intensive industries, shipping and aviation still emitting heavily in 2050. The Deeper Decarbonisation Perspective highlights options to get such sectors to zero. While much remains to be seen, an estimated 60% of the reductions in this final stretch could come from renewables, "green hydrogen" and renewable-based electrification.

Low-carbon investment options

- **Energy-related CO_2 emissions have risen by 1% per year over the past decade.** While the health shock and oil slump may suppress emissions in 2020, a rebound would restore the long-term trend.

- **The Transforming Energy Scenario instead offers a climate-safe path, sufficient to keep global warming this century "well below 2°C" in line with the Paris Agreement.** It could also help to guide continual updates of national climate pledges, which can be strengthened with enhanced renewable energy targets.

- **This outlook for the transformation of the energy system also indicates higher GDP growth, achieving 2.4% more by mid-century than current plans would achieve.** The cumulative gain between now and 2050 amounts to USD 98 trillion, greatly exceeding the additional investments needed for transforming the energy system.

- **The envisaged transformation would effectively pay for itself, with every dollar spent bringing returns between three and eight dollars.** The Transforming Energy Scenario would cost USD 19 trillion more than the Planned Energy Scenario, while bringing benefits worth at least USD 50 trillion by 2050. The Deeper Decarbonisation Perspective would cost another USD 16 trillion to achieve net-zero emissions, or another USD 26 trillion to fully eliminate CO_2 emissions, for a total cost of USD 45 trillion, yet cumulative savings would still be higher at USD 62 trillion or more.

- **Along with a sustainable energy future, the transition promises new patterns of socio-economic development.** The changing investment focus in this outlook would increase jobs in renewables to 42 million globally by 2050, four times more than today. Energy jobs overall would reach 100 million by 2050, about 40 million more than today. The transition would result in 7 million more jobs economy-wide compared to current plans. Environmental and health benefits, along with broad improvements in people's welfare, would be felt in every region of the world.

- **People's well-being would improve faster and further, with a 13.5% higher welfare indicator under the Transforming Energy Scenario by 2050.** The divergence mainly reflects of lower air pollution, which would result in better health across every region. Everywhere, the transition promises to improve people's welfare.

Co-ordination for a smooth transition

- **Ramping up regional ambitions will be crucial to meet interlinked energy and climate goals.** Renewables, efficiency and electrification provide a clear focus for action to cut the bulk of emissions at the regional and country levels. Despite varied transition paths, all regions would see higher shares of renewable energy use, with Southeast Asia, Latin America, the European Union and Sub-Saharan Africa poised to reach 70-80% shares in their total energy mixes by 2050. Similarity, electrification of end uses like heat and transport would rise everywhere, exceeding 50% in East Asia, North America and much of Europe.

- **Despite clear global gains, the transition's structural and labour-market impacts will vary among locations, job types and sectors.** As renewables, energy efficiency and other transition-related sectors grow, other energy jobs will decline. But strategies to ensure a just transition could help to minimise dislocations for individuals and communities.

- **Different socio-economic starting points will contribute to different regional energy transitions.** On-the-ground impact will stem from dependence on fossil fuels and other commodities, pre-existing industrial productivity, evolving technology choices, and the depth and diversity of domestic supply chains. Regional and national transition plans, institutional structures, capabilities and policy ambitions also vary, bringing different results in 2050.

- **Rapid decarbonisation calls for unprecedented policy initiatives and investments.** The Climate Investment Platform announced in 2019 aims to drive clean energy uptake in line with Paris Agreement goals. Sub-regional investment forums will help to create the right conditions, improve access to finance and prepare bankable projects.

- **Completing the global energy transition in time to stave off catastrophic climate change requires intensified international co-operation.** The aim is to enable governments and other institutions to adopt a wide array of ambitious policies, all aimed at strengthening public resolve and ensuring that no one is left behind.

- **Ultimately, success in mitigating the climate threat will depend on the policies adopted, the speed of their implementation and the level of resources committed.** Moving forward, investment decisions could be assessed based on their compatibility with building an inclusive low-carbon economy. Anything less would hinder the transformative decarbonisation of societies.

GLOBAL RENEWABLES OUTLOOK: SUMMARY

A WIDENING GAP BETWEEN RHETORIC AND ACTION

Main report **Chapters 1 and 5**

The gap between aspiration and the reality in tackling climate change remains as significant as ever, despite mounting evidence of the harm that climate change is causing. Negative effects of climate change are becoming more evident year by year (NASA, WMO, 2020). Yet global energy-related CO_2 emissions, despite levelling off periodically, have risen by 1% per year on average over the last decade.

The distribution of efforts among countries remains uneven, with certain countries pursuing net-zero emissions while others continue to lack policy targets. Government plans have yet to fully capture the reality of the markets. Nationally Determined Contributions (NDCs) within the Paris Agreement framework are in many cases less ambitious than the latest energy plans and market developments. According to IRENA estimates, current NDC power targets only cover 40% of the renewable electricity deployment needed by 2030 to set the world on course to meet key climate goals (IRENA, 2019b).

The health, humanitarian, social and economic crises set off by the current COVID-19 pandemic could either widen the gap or accelerate the decarbonisation of our societies. Much will depend on how countries respond in terms of economic stimulus. The challenges of ensuring sustainability, strengthening resilience and improving people's health and welfare will be paramount. The **Transforming Energy Scenario** (TES) identified in this report shows how to achieve stable, climate-safe, sustainable long-term energy and economic development. The resulting outlook – further enhanced by the **Deeper Decarbonisation Perspective** (DDP) – could guide low-carbon policy measures, helping to ensure coherence between rhetoric and action in tackling climate change.

This report presents several possible scenarios for the evolution of energy-related CO_2 emissions. In the Baseline Energy Scenario (BES), energy-related emissions increase by a compound annual rate of 0.7% per year to 43 gigatonnes (Gt) by 2050 (up from 34 Gt in 2019), resulting in a likely temperature rise of 3°C or more in the second half of this century. The Planned Energy Scenario (PES), or main reference case, sees emissions increase slightly by 2030 and then decline to 33 Gt, roughly today's level, by 2050. This would result in a likely global temperature rise of 2.5°C in the second half of this century. IRENA's **Transforming Energy Scenario**, in contrast, sees emissions fall at a compound rate of 3.8% per year to some 10 Gt, or 70% less than today's level, by 2050, keeping the expected temperature rise well below 2°C.

The **Deeper Decarbonisation Perspective** would reduce emissions to zero by as early as 2050 or latest by 2060, consistent with holding the line at 1.5°C.

Recent energy trends confirm the need to accelerate a reduction in CO_2 emissions. Renewable energy forms a key part of any viable solution. Renewable energy shares, the energy intensity of GDP and the electrification of final uses of energy have all shown improvements in recent years, yet the pace of those improvements does not put the world on track to meet the goals of the Paris Agreement. Efforts are also needed to reduce emissions outside the energy sector.

Fossil fuels continue producing negative effects in many parts of the world. These include high levels of air, water and soil pollution, and persistent energy-import dependence. Currently, air pollution causes 7 million premature deaths per year (WHO, 2020). With an estimated 840 million people still lacking access to electricity and 2.6 billion lacking access to clean cooking fuels, the world has a pressing need for clean, sustainable energy solutions. For now, some regions are increasing their dependency on energy imports (IEA, IRENA, UNSD, World Bank, WHO, 2019).

The Transforming Energy Scenario would cut fossil-fuel use by about 75% by mid-century. Looking ahead under the Planned Energy Scenario, primary energy demand increases from around 600 exajoules (EJ) today to 710 EJ by 2050 (see Figure S.1), yet the amount of fossil fuels remains roughly similar to today's level, showing the increasing role renewable energy plays. However, given the need to reduce emissions, fossil-fuel consumption cannot stay at today's level. In the Transforming Energy Scenario it declines by 75% compared to today's level, to 130 EJ by 2050 – roughly equivalent to just the energy demand of China today. The largest consumption declines would take place in coal, down by 41% and 87% in 2030 and 2050, respectively. Oil would see the second largest declines, of 31% and 70% in 2030 and 2050, respectively. Natural gas would have an increase of 3% by 2030 (the Planned Energy Scenario has natural gas growth of over 40% by 2030), but it would decline 41% by 2050.

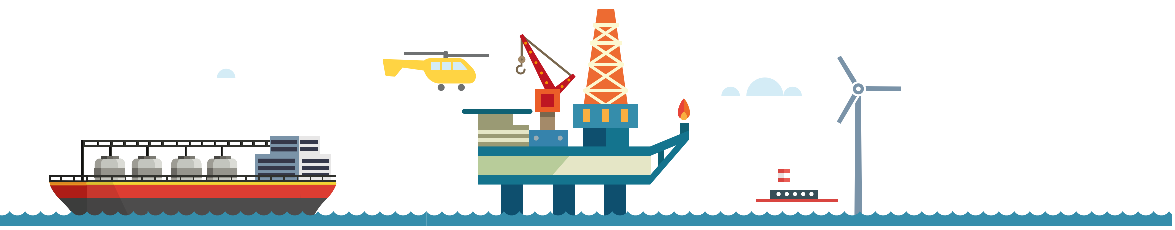
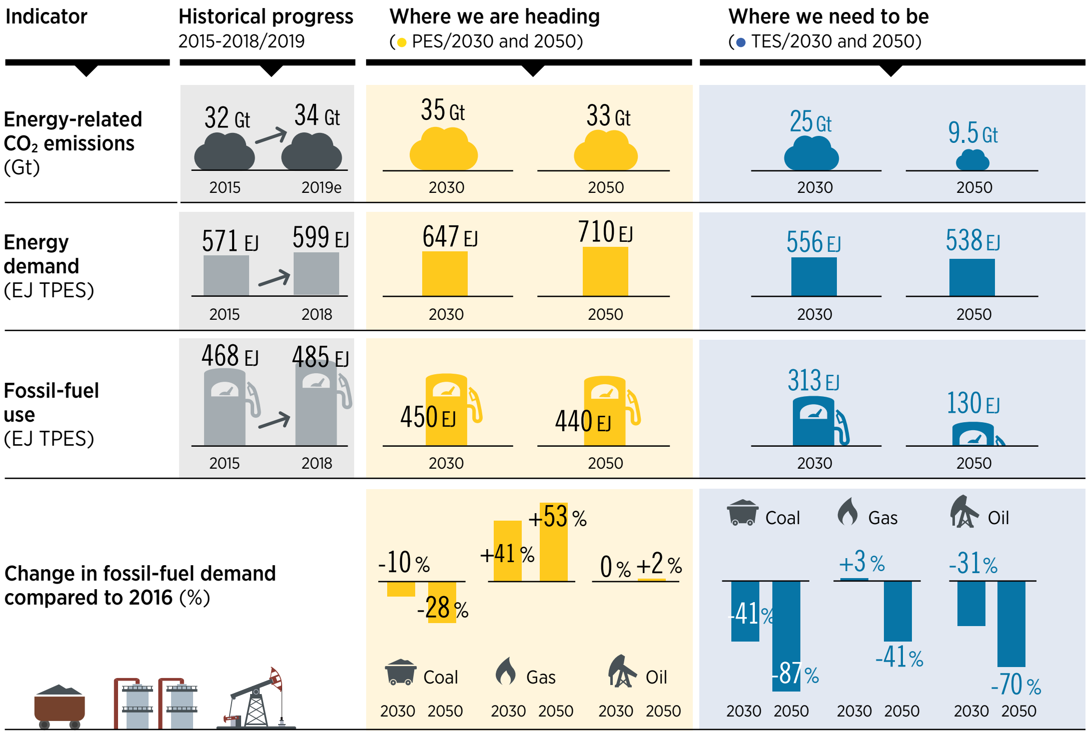


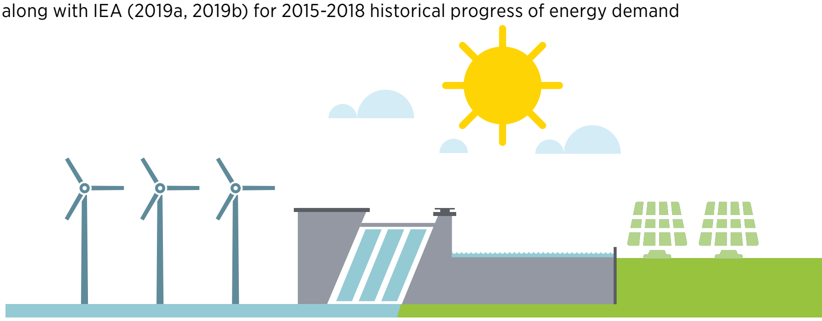
Figure S.1. The changing nature of energy and fossil-fuel use

Energy-related CO_2 emissions, energy demand and fossil-fuel outlook



Note: TPES = total primary energy supply. e = estimate; Gt = gigatonnes; EJ = exajoules.

Based on IRENA scenarios (PES and TES), along with IEA (2019a, 2019b) for 2015-2018 historical progress of energy demand and fossil-fuel use.



Main report **Chapters 1 and 5**

TRANSFORMATIVE ENERGY DEVELOPMENTS

The energy sector has started changing in promising ways, with widespread adoption of renewables and related technologies boding well for a sustainable future. Renewable technologies are dominating the global market for new power generation capacity. Solar PV and wind are increasingly the cheapest source of electricity in many markets, and most renewable power sources will be fully cost competitive within the next decade (IRENA, 2019c).

Renewable power generation is now growing faster than overall power demand. A new milestone was reached in 2019 when renewable electricity generation increased by more than the increase in electricity demand, while fossil-fuel electricity generation decreased. This is the first time in decades that fossil-fuel-based generation declined when overall electricity generation increased (Kåberger, 2019).

The electrification of transport is showing early signs of disruptive acceleration. Progress in accelerating the transition is seen in the rapid cost reductions of solar PV and wind (including offshore), how key enabling technologies such as batteries and electric vehicles are experiencing rapid reductions in costs, and how green hydrogen is viewed as a potential game changer.

Yet renewables are growing too slowly in major energy-consuming sectors like buildings and industry. Deployment in these areas remains well below the levels needed to create a climate-safe energy system. Slowing progress in energy efficiency and biofuels development must be turned around quickly.

The share of modern renewable energy in global final energy consumption has increased only slightly since 2010, staying around a threshold of about 10%.[1] In simple terms, while renewables are increasing, so is energy demand. In the Planned Energy Scenario, the share of modern renewable energy in final energy supply would increase to 17% by 2030 and 25% by 2050. In the Transforming Energy Scenario, this share would increase to 28% by 2030 and 66% by 2050. Therefore, the share would need to increase six-fold compared to today, and two-and-a-half times compared to the Planned Energy Scenario.

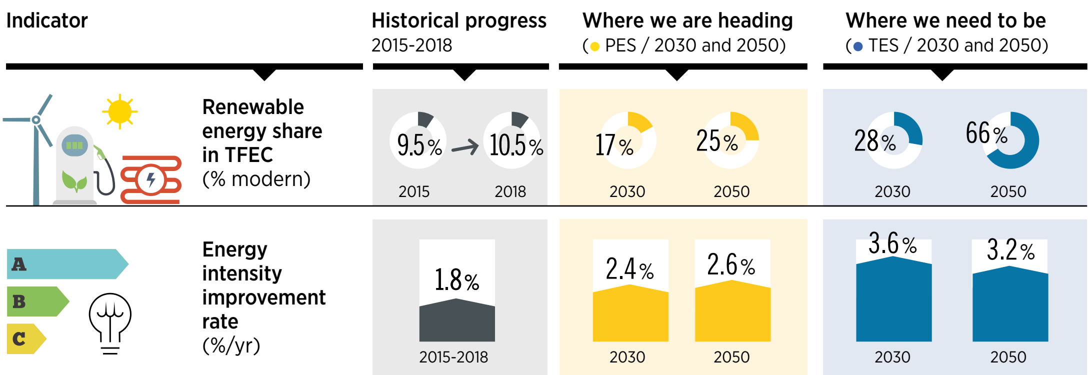
[1] Modern renewable energy excludes traditional uses of bioenergy, which if included in this share would bring the share of all renewable energy in total final energy to 18%.

Energy efficiency improvements must be scaled up rapidly and substantially. Energy efficiency and renewable energy are the two key solutions to enable the global energy transformation. Yet the improvement in energy intensity has slowed. The improvement in 2019 was only an estimated 1.2%, less than the average of 1.8% per year over the last decade (IEA, 2019a). In the Transforming Energy Scenario, the rate of energy intensity improvement needs to increase to 3.2% per year, nearly three times the improvement during 2019 and roughly double compared to recent historical trends. Renewable energy and energy efficiency are "ready-to-go" solutions, available for significant scale-up now.

Renewable energy and energy efficiency together offer over 90% of the mitigation measures needed to reduce energy-related emissions in the Transforming Energy Scenario. To achieve this reduction energy-related CO_2 emissions need to fall by 3.8% per year on average until 2050, to 70% below today's level. That compares to an average annual increase of 1% over the last decade, with a flatlining in 2019. Figure S.2 shows the share of renewable energy and the energy efficiency improvement rate that is needed to achieve the necessary reductions.

Figure S.2. Renewables in the world's energy mix: Six-fold increase needed

Renewable energy share and energy efficiency improvement rate



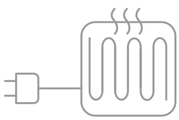
Based on IRENA scenarios (PES and TES), along with IEA (2019a, 2019b) for 2015-2018 historical progress of energy share in total final energy consumption (TFEC).

Five technology pillars for the future of energy

FIRST PILLAR: ELECTRIFICATION

Renewable power generation technologies are setting records for low costs and new capacity despite falling renewable energy subsidies and slowing global GDP growth. In the Transforming Energy Scenario, electricity would become the central energy carrier by 2050, growing from a 20% share of final consumption to an almost 50% share; as a result, gross electricity consumption would more than double.

The rate of growth in the percentage share of electricity (percentage point "ppt") in final energy needs to quadruple, from an increase of 0.25 ppt/yr to 1.0 ppt/yr. To put this into perspective, an additional 1 000 terawatt-hours (TWh) of electricity demand for electrification of end uses has to be added every year on top of current plans – equivalent to adding the entire electricity generation of Japan every year. To supply this additional renewable electricity demand, over 520 gigawatts (GW) of new renewable capacity would need to be added per year. In parallel, the share of renewable electricity in generation has to rise from 26% currently to 57% by 2030 and 86% by 2050. This rise is being accelerated by declining costs: four-fifths of solar PV and wind projects to be commissioned in 2020 will produce electricity cheaper than any fossil-fuel alternative (IRENA, 2019c).



The electrification of end uses will drive increased power demand to be met with renewables. In the transport sector, the number of electric vehicles (EVs) will increase from around 8 million in 2019 to over 1 100 million in the Transforming Energy Scenario by 2050 (see Figure S.3). For heating, heat pumps offer efficiency gains ranging from two to four times higher than conventional heating systems, and the number of heat pumps installed by 2050 would need to increase 10-fold. The shift to these highly efficient electrification technologies also brings increases in energy efficiency.

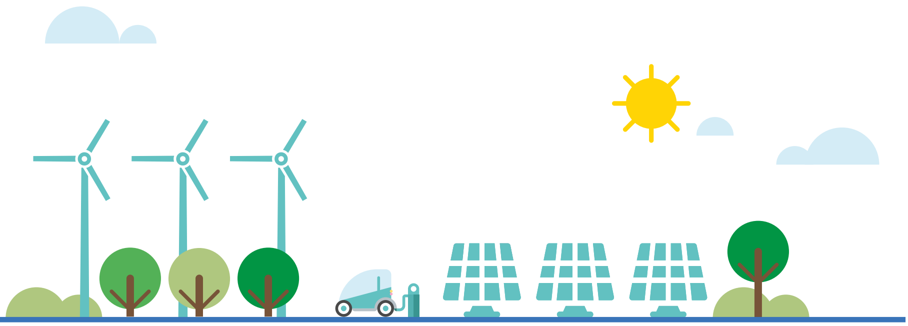


Figure S.3. An increasingly electrified energy system

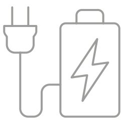
Renewable electricity share in electricity generation, electrification share, and select technologies

Indicator	Historical progress 2015-2018/2019		Where we are heading (PES/2030 and 2050)		Where we need to be (TES/2030 and 2050)	
Renewable share in electricity generation (%)	23% (2015)	26% (2018)	38% (2030)	55% (2050)	57% (2030)	86% (2050)
Electrification share of final energy (%)	19% (2015)	20% (2017)	24% (2030)	30% (2050)	29% (2030)	49% (2050)
Technologies						
Electric cars (mln units)	1.2 mln (2015)	7.9 mln (2019e)	269 mln (2030)	627 mln (2050)	379 mln (2030)	1 109 mln (2050)
Heat pumps (mln units)	20 mln (2017)	38 mln (2019e)	63 mln (2030)	119 mln (2050)	155 mln (2030)	334 mln (2050)

Based on IRENA scenarios (PES and TES), along with Spiegel (2020), IEA (2019a, 2019b), IEA and IRENA (2017) and IRENA (2019a) for 2015-2018 historical progress.

SECOND PILLAR:
INCREASED POWER SYSTEM FLEXIBILITY

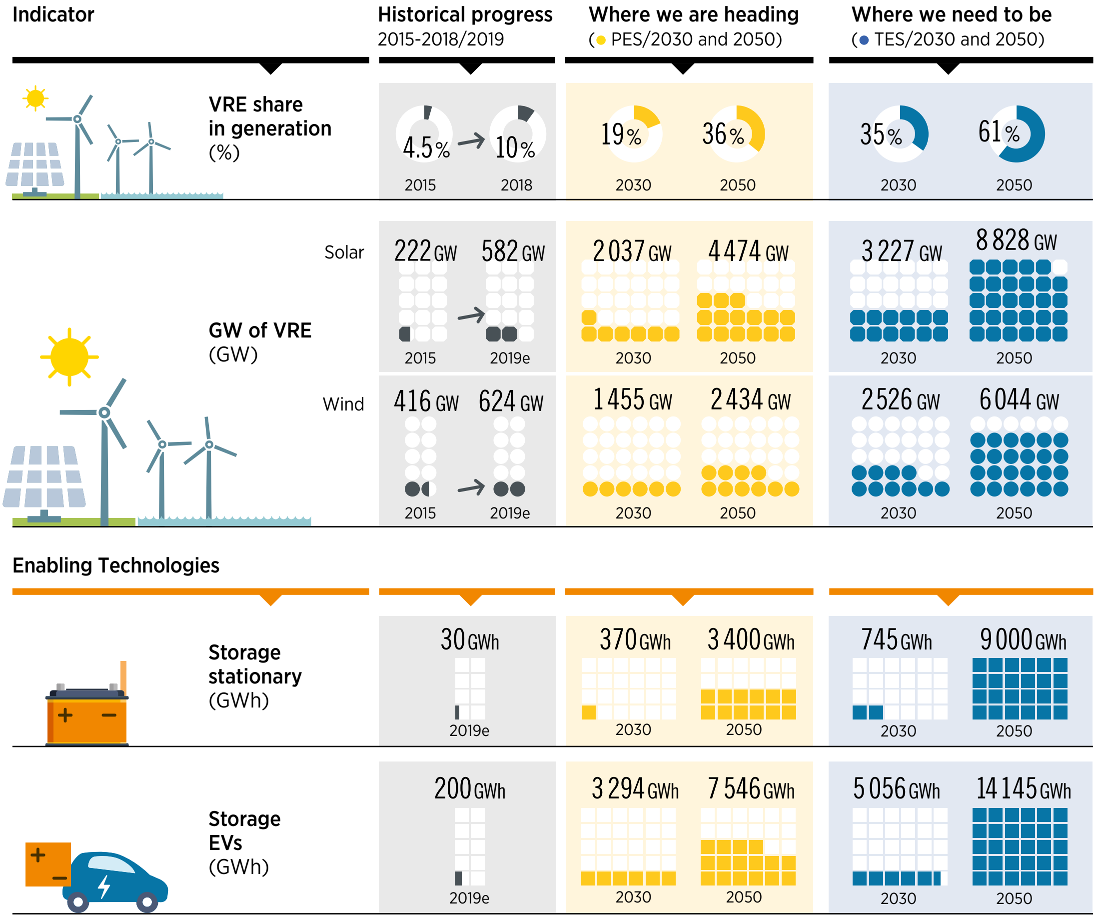
Flexibility in power systems is a key enabler for the integration of high shares of variable renewable electricity – the backbone of the electricity system of the future. A climate-friendly energy system is decentralised, digitalised and electrified. Today, countries are integrating variable renewable energy (VRE) at a share of over 30% on an annual basis (and in some cases much higher), which means that instantaneous penetration of VRE can, at times, approach, or even exceed, electricity demand. These periods of electricity surpluses can then offer new business opportunities for further electrification. In the Transforming Energy Scenario, 73% of the installed capacity and over 60% of all power generation would come from variable resources (solar PV and wind), up from 10% of power generation today.



Power systems must achieve maximum flexibility, based on current and ongoing innovations in enabling technologies, business models, market design and system operation. On a technology level, both long-term and short-term storage will be important for adding flexibility, and the amount of stationary storage (which excludes EVs) would need to expand from around 30 gigawatt-hours (GWh) today to over 9 000 GWh by 2050 (see Figure S.4). When storage available to the grid from the EV fleet is included, this value will increase by over 14 000 GWh to 23 000 GWh. However, most flexibility will still be achieved through other measures, including grid expansion and operational measures, demand-side flexibility and sector coupling. IRENA estimates that smart solutions, such as smart charging of EVs, can significantly facilitate the integration of VRE by leveraging storage capacity and the flexibility potential of the demand side. Investment in end-use electrification, power grids and flexibility will need to increase from USD 13 trillion in the Planned Energy Scenario to USD 26 trillion in the Transforming Energy Scenario over the period to 2050.

Figure S.4. The need for power system flexibility

VRE share in generation and capacity, storage technologies



Based on IRENA scenarios (PES and TES), along with Bohlsen (2020), GWEC (2020), IEA (2019a) and IRENA analysis and IRENA (2019d, 2019f) for 2015-2018 historical progress.

THIRD PILLAR: CONVENTIONAL RENEWABLE SOURCES

Hydropower, bioenergy, solar thermal and geothermal renewable energy all have significant scale-up potential and represent over one-quarter of the mitigation potential in the Transforming Energy Scenario. Two technologies that can play particularly important roles are hydropower and bioenergy.

Hydropower can bring important synergies to the energy system of the future. In the Transforming Energy Scenario, hydropower capacity would need to increase 25% by 2030, and 60% by 2050, while pumped hydro storage capacity would need to double. When including both types of hydropower, around 850 GW of newly installed capacity is required in the next 30 years – or roughly adding the entire power system capacity of the European Union in 2020. The synergies between hydropower and other renewable energy technologies in power system operation include the cost effectiveness of using hydropower to counteract the short-term variability of wind and solar generation, and seasonal complementarities in resource patterns. Multi-purpose hydropower infrastructure also can provide co-benefits such as regulating river flows and reducing flooding.

Increasing hydropower capacity does not specifically entail only building new dams: options also exist to upgrade turbines and systems in existing plants, utilise run-of-river designs and electrify non-power dams. Yet for new hydropower plants, planners need to consider local environmental impacts, and engage in discussions with communities in the impacted areas. Hydropower plants will also need operational changes that reflect changing power system needs, including faster and more frequent ramping, and planning practices that include evaluating the impacts of climate change on water supply and reservoir storage requirements. Due to longer planning cycles for new hydropower dam construction, policy makers and planners need to start thinking now about new projects. For existing dams, investments are needed to modernise old hydro plants.

Bioenergy will become increasingly vital in end-use sectors. Bioenergy makes up a large share of renewable energy use today and will remain a significant source of fuel for power and heat generation in industry and as a fuel used in transport. The share of primary energy that is met with modern bioenergy (which excludes traditional uses of biofuel) will increase from 5% today to 10% in the Planned Energy Scenario. In the Transforming Energy Scenario, bioenergy plays an important role, particularly in sectors that are hard to electrify, such as in shipping and aviation and in industry, both for process heat and use as a feedstock. In the Transforming Energy Scenario, the share of primary energy met with modern bioenergy increases to 23% (see Figure S.5). Meanwhile, traditional uses of bioenergy, which cover a large share of bioenergy demand today, must be phased out and replaced with cleaner options, including modern bioenergy and other renewables.

Bioenergy must be produced in ways that are environmentally, socially and economically sustainable. The potential is enormous to produce bioenergy cost effectively and sustainably on existing farmlands and grasslands, and to use residues from existing production forests without encroaching upon rainforests. Bioenergy from such sources would make use of surplus crop potential and not threaten food production (IRENA, 2016a).

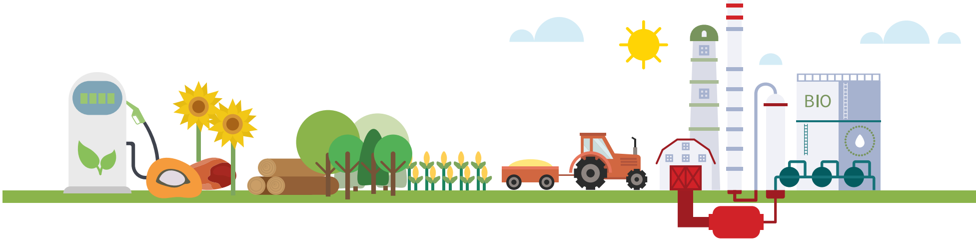
Figure S.5. Vital to any future energy system: Hydropower and bioenergy

Hydropower capacity, bioenergy shares, and liquid biofuel production

Indicator	Historical progress 2015-2017/2018/2019	Where we are heading (PES/2030 and 2050)	Where we need to be (TES/2030 and 2050)
Hydropower (GW)	1 099 GW (2015) → 1 189 GW (2019)	1 356 GW (2030); 1 626 GW (2050)	1 444 GW (2030); 1 822 GW (2050)
Pumped hydro storage (GW)	112 GW (2015) → 121 GW (2019)	200 GW (2030); 300 GW (2050)	225 GW (2030); 325 GW (2050)
Share of TPES provided by bioenergy (%) **(total)**	8.7% (2015) → 9.5% (2018)	9% (2030); 10% (2050)	12% (2030); 23% (2050)
Share of TPES provided by bioenergy (%) **(modern)**	4.1% (2015) → 5.1% (2018)	8% (2030); 10% (2050)	12% (2030); 23% (2050)
Liquid biofuel production (bln litres)	129 bln ltr (2015) → 136 bln ltr (2017)	285 bln ltr (2030); 393 bln ltr (2050)	378 bln ltr (2030); 652 bln ltr (2050)

Based on IRENA scenarios (PES and TES), along with Bohlsen (2020), IEA (2019s), IRENA (2019d, 2019e, 2019f) and IRENA analysis for 2015-2018 historical progress.

Note: The total bioenergy share includes traditional uses of biofuels. In PES their use is reduced considerably by 2030, but not entirely phased out, whereas in PES their use is entirely phased out by 2030.
TPES = total primary energy supply



FOURTH PILLAR: GREEN HYDROGEN

Hydrogen can offer a solution for types of energy demand that are hard to directly electrify. Today, around 120 megatonnes (Mt) (14 EJ) of hydrogen is produced per year (IRENA, 2019g). But almost all of this comes from fossil fuels or from electricity generated by fossil fuels, with a high carbon footprint; less than 1% is "green" hydrogen. Yet progress is being made and in early 2020 the world's largest green hydrogen production plant with 10 MW electrolyser capacity began operation in Japan (Recharge, 2020).

Green hydrogen is produced by renewable electricity through electrolysis, and costs are falling fast. Green hydrogen will become cost competitive with "blue" hydrogen (produced from fossil fuels combined with carbon capture and storage [CCS]) in the next few years in locations with favourable low-cost renewable electricity. As costs fall further, green hydrogen will be cheaper than blue hydrogen in many locations within the next 5 to 15 years. Certain energy-intensive industries may in the future relocate to areas with good renewable energy resources to tap this potential to produce cheap green hydrogen; examples include iron making and ammonia. The first plant producing ammonia from green hydrogen is expected to open in 2020 (Yara, 2019).

Hydrogen can be processed further into hydrocarbons or ammonia, which can then help reduce emissions in shipping and aviation. The natural gas industry is also looking at hydrogen as a promising solution for greening the gas system and extending the life of existing infrastructure. However, this approach must be viewed with caution in light of unclear prospects of actually being able to significantly reduce emissions of the gas system and the potential to lock in carbon-intensive infrastructure. A hydrogen commodity trade is nascent, but hydrogen could become the clean energy vector that makes it possible to tap into ample remote, low-cost renewable energy resources – a development that could have important geopolitical implications as well as further accelerating the demand for renewable power generation. By 2050, there would be 160 Mt (19 EJ) of green hydrogen produced annually in the Transforming Energy Scenario (see Figure S.6). That amount, however, would only cover 5% of global energy demand today, with an additional 2.5% being met with blue hydrogen. Significant scale-up of electrolysers is necessary to produce that amount, requiring additions of between 50 GW and 60 GW per year of new capacity from now until 2050.

Figure S.6. Hydrogen: A key part of future energy systems

Evolving hydrogen production, costs and electrolyser capacity

Indicator	Historical progress 2015-2018	Where we are heading (PES / 2030 and 2050) 2030	Where we are heading 2050	Where we need to be (TES / 2030 and 2050) 2030	Where we need to be 2050
Blue H_2 (Mt and EJ)	0.6 Mt / 0.08 EJ (2015 - 2018)	10 Mt 1.25 EJ	40 Mt / 5 EJ	30 Mt 3.75 EJ	80 Mt / 10 EJ
Green H_2 (Mt and EJ)	1.2 Mt / 0.16 EJ (2015 - 2018)	9 Mt 1.1 EJ	25 Mt / 3 EJ	25 Mt / 3 EJ	160 Mt / 19 EJ
Green H_2 production costs (USD/kg)	4.0 - 8.0 USD/kg (2015 - 2018)	2.5 - 5.0 USD/kg	1.6 - 3.3 USD/kg	1.8 - 3.2 USD/kg	0.9 - 2.0 USD/kg
Electrolysers (GW)	0.04 GW (2016)	100 GW	270 GW	270 GW	1 700 GW
Electricity demand to produce H_2 from renewables (GW)	0.26 TWh (2016)	450 TWh	1 200 TWh	1 200 TWh	7 500 TWh

Based on IRENA analysis

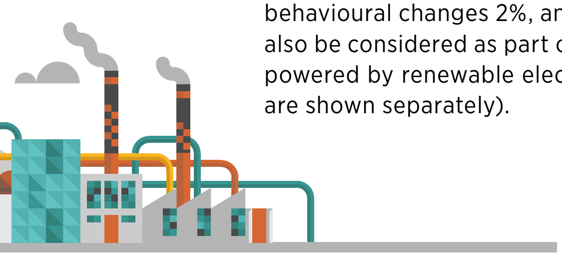
Note: Hydrogen produced from fossil fuels without CCS is called grey hydrogen, with CCS is called blue hydrogen, and if made from renewable power through electrolysis it is called green hydrogen. RE = Renewable Energy

FIFTH PILLAR:
FOSTER INNOVATION TO ADDRESS CHALLENGING SECTORS

In the Transforming Energy Scenario, half of energy demand could be supplied by electricity by 2050, but the remaining half must also be considered. Of this, one-third is already supplied by end-use renewable sources, with the remaining two-thirds by fossil fuels. Solutions to further reduce fossil-fuel use include increased direct use of renewable energy (bioenergy, solar thermal, geothermal heat), energy efficiency and structural changes that can reduce energy demand, and deeper electrification. However, more will still be needed, in particular for sectors such as shipping, aviation and heavy industry. To put it in perspective, three-quarters of the remaining emissions in the Transforming Energy Scenario in 2050 are from the aviation, shipping and heavy industry sectors.

This report presents views on how reduce these remaining emissions in the Deeper Decarbonisation Perspective (DDP). The Deeper Decarbonisation Perspective is not a scenario in itself, rather it is an enhancement of additional technology options on top of the Transforming Energy Scenario. In challenging sectors such as freight, shipping, aviation and heavy industry, advances in biofuels, synthetic fuels, new materials and the circular economy will all be necessary. Industry is the dominant energy consumption sector in many countries such as China, where the sector consumes around half of final energy. There is an urgent need to find solutions for key sectors, such as iron and steel, cement and petrochemicals, which make up the bulk of industry energy demand. Innovation is also needed to find zero CO_2 emission solutions for industrial process emissions and for non-energy uses in these sectors. Innovation will also continue to be crucial to address transport modes that are hard to electrify, namely aviation and shipping.

The Deeper Decarbonisation Perspective shows how the remaining energy and industrial process-related CO_2 emissions in the Transforming Energy Scenario can be cut to zero. Renewable energy provides 60% of the reduction needed when including renewables, green hydrogen and renewables-based electrification; 37% of reductions come from energy efficiency and other structural and behavioral changes; and the remaining 3% of reductions come from carbon capture, utilisation and storage (CCUS) and nuclear. Overall, when considering reductions in energy and industrial process-related CO_2 emissions from the Baseline Energy Scenario to zero, renewables make up 43% of the reductions, energy efficiency 26%, EVs 12%, green hydrogen 9%, blue hydrogen and CCS/Carbon dioxide removal (CDR) 7%, behavioural changes 2%, and nuclear under 1% (EVs and behavioural changes could also be considered as part of energy efficiency, or for the case of EVs, renewables if powered by renewable electricity. However, to show their relative importance they are shown separately).



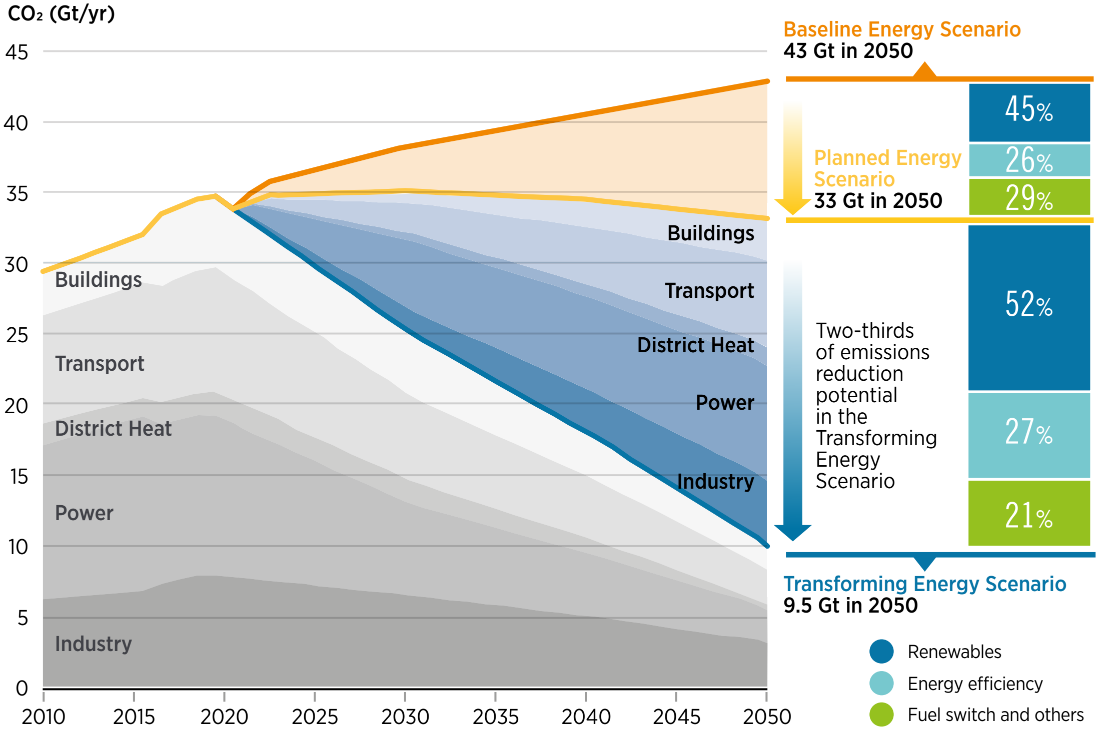
PLANNING FOR THE LONG TERM

Main report **Chapter 1, 3 and 5**

To achieve the Energy Transformation Scenario, energy-related CO_2 emissions need to fall by 3.8% per year on average until 2050. Annual energy-related CO_2 emissions would need to decline by 70% below today's level by 2050. In the Transforming Energy Scenario by 2050, over half of the necessary reductions in emissions come from renewable energy (both power and end use), followed by around one-quarter coming from energy efficiency (see Figure S.7). When including direct and indirect electrification (such as green hydrogen and technologies like EVs), the total reductions increase to over 90% of what is required. The Deeper Decarbonisation Perspective then describes how reducing the remaining emissions to zero – over two-thirds of which come from challenging sectors such as aviation, shipping and heavy industry – will require additional renewable energy, electrification (both direct use and green hydrogen), energy efficiency, carbon management, and other structural and habit changes. Outside the energy sector, efforts also are needed to reduce emissions from non-energy use, emissions from land use, land-use change and forestry (LULUCF), and fugitive gases in the coal, oil and gas industries.

Figure S.7. The bulk of emission reductions: Renewables and efficiency

Energy-related CO_2 emissions, 2010-2050

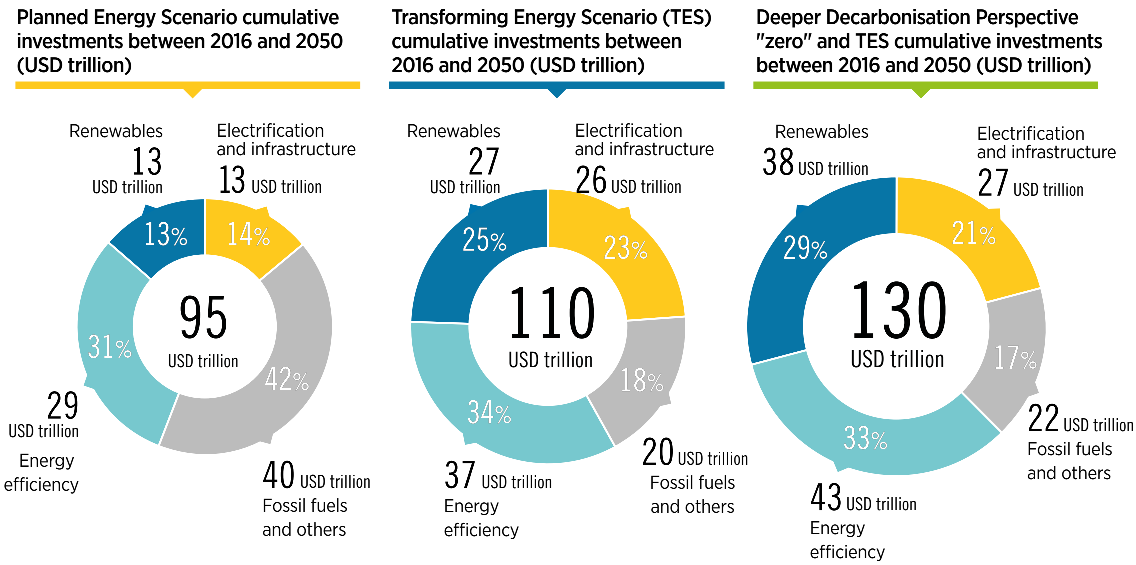


Based on IRENA analysis

A climate-safe future calls for the scale-up, and redirection, of investment to clean energy technologies. Fossil-fuel investments need to be shifted to renewables and energy efficiency instead, while subsidies to fossil fuels must be phased out. Overall, total investment in the energy system in the Transforming Energy Scenario would need to reach USD 110 trillion by 2050, or around 2% of average annual GDP over the period (see Figure S.8). Of that total, over 80% needs to be invested in renewables, energy efficiency, end-use electrification, and power grids and flexibility. If viewed in annual terms, USD 3.2 trillion needs to be invested in the global energy system every year to 2050. That compares to recent historical investment (2014-2018) in the energy system of around USD 1.8 trillion per year (IEA, 2019c), and USD 2.9 trillion per year in the Planned Energy Scenario.

The Deeper Decarbonisation Perspective would require additional investment of USD 20 trillion over the USD 110 trillion of investments in the Transforming Energy Scenario, for a total investment need of USD 130 trillion to reach zero emissions. To help navigate these new investment "waters", and to accelerate a shift of finance into climate-friendly technologies, IRENA is working with partners on the Climate Investment Platform (CIP) to unlock financial resources for the clean energy transition, particularly in developing countries. By addressing the key risks and barriers that hinder the scale-up of renewable investment, CIP will accelerate the low-carbon energy transition and promote sustainable growth.

Figure S.8. New investment priorities: Renewables, efficiency and electrification of heat and transport



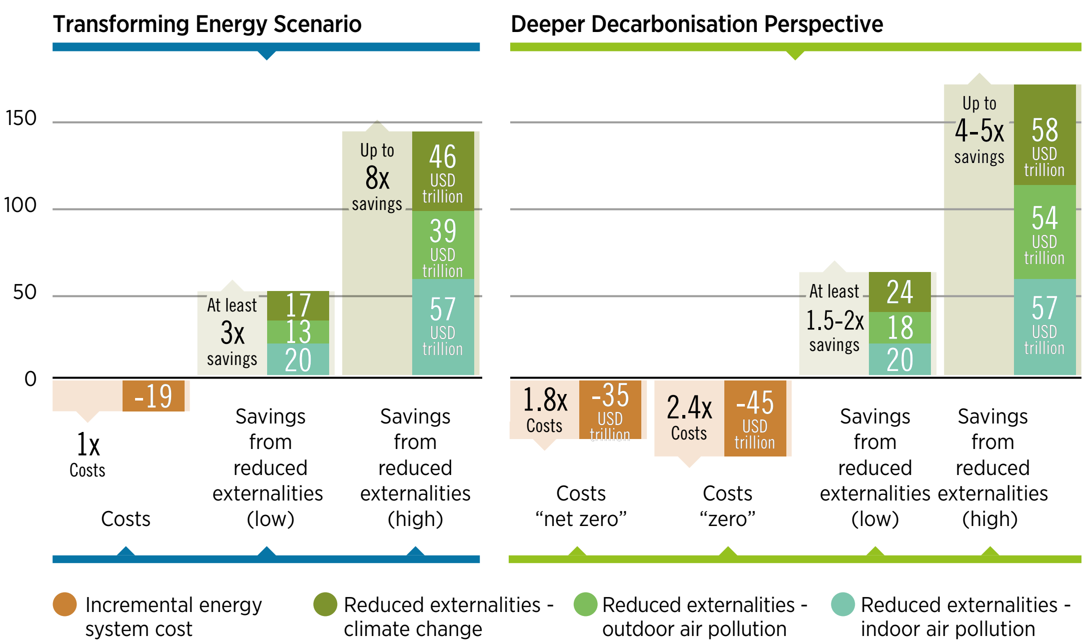
Based on IRENA analysis

The payback for accelerating renewables deployment and efficiency measures is many times larger than the costs. In the Transforming Energy Scenario, every USD 1 spent for the energy transition would bring a payback of between USD 3 and USD 8 (see Figure S.9). Or to put it in cumulative terms, the Transforming Energy Scenario would have an additional cost of USD 19 trillion over the period to 2050 but would result in a payback of between USD 50 trillion and USD 142 trillion in reduced environmental and health externalities. The Deeper Decarbonisation Perspective would cost an additional USD 16 trillion to achieve net-zero emissions, or an additional USD 26 trillion to achieve fully zero emissions (with no carbon offsets).

Therefore, the total additional costs to reach zero range from USD 35 to USD 45 trillion. Yet these higher costs are still significantly lower than the USD 62 to USD 169 trillion in savings from reduced externalities that would result from reaching zero emissions. Another way to look at costs is how much it takes to mitigate one tonne of CO_2 over the period. For the Transforming Energy Scenario, this cost would be USD 34/t CO_2. For the DDP net-zero, the cost would be USD 100/t CO_2, and for DDP fully zero, it would be USD 156/t CO_2.

Figure S.9. The energy transition: Benefits compared to costs

Cumulative system costs and savings from reduced externalities for Transforming Energy Scenario for the period to 2050, and DDP for the period to 2060 (USD trillion)

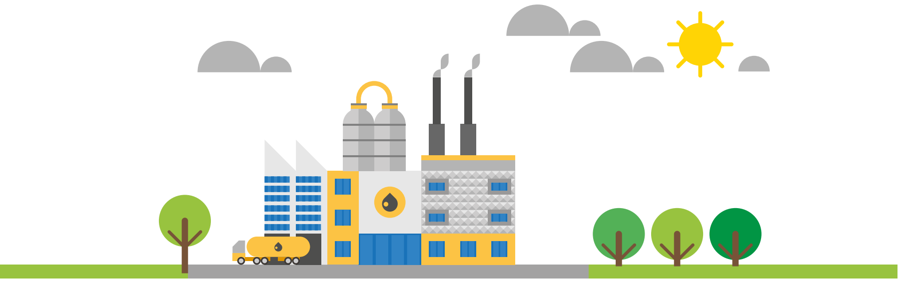


Based on IRENA analysis

Climate change may have significant detrimental and destabilising effects on the world's financial system. Fires, floods, drought, extreme weather, rising seas and other impacts of climate change will take an increasing economic, environmental and human toll – which must be borne in the end by taxpayers, governments and communities (IMF, 2019). In addition, the health costs of pollution are increasingly of major concern for many cities, particularly in the developing world. Central banks, financial institutions and insurance companies are starting to take note and to incorporate assessments of climate risk into their financial planning. Key institutions that have announced steps to incorporate climate risk include the International Monetary Fund, Blackrock, Norway's sovereign wealth fund and KfW Group.

Investments that continue to expand fossil-fuel supply infrastructure are short-sighted and increasingly risky. Such investments will lead to significant stranded assets and will lock in fossil-fuel emissions for decades to come that will also risk achieving the aims of the Paris Agreement (Tong *et al.*, 2019). Recent low oil prices serve as a reminder of the volatility of markets for oil – and other fossil fuels – and of the geopolitics associated with our current energy system. Existing renewable technologies, energy efficiency and some emerging renewables-based technologies can take the reins instead and supply energy across a wide range of energy services at lower cost than fossil fuels, especially when they are coupled with expensive, and often unproven, carbon removal or recycling technologies. While some action is necessary to explore opportunities to make existing fossil-fuel assets cleaner and lower carbon, particularly in sectors such as in industry, where some CCS may be necessary, governments and investors should generally avoid investments into new fossil-fuel supply infrastructure.

Due to the slow progress to date in reducing emissions from the energy sector, already USD 11.8 trillion in assets will need to be stranded by 2050 in the Transforming Energy Scenario. Moreover, further delaying action for another 10 years would result in an additional USD 7.7 trillion in stranded assets by 2050. Limiting the amount of future stranded assets requires greater attention today on the risks that companies, banks and investors face from climate change and the response to climate change. One effort to make those risks more visible is the Task Force on Climate-Related Financial Disclosure, which is helping to develop voluntary climate-related financial risk disclosures.



Policy makers need to establish long-term integrated energy planning strategies, define targets, and adapt policies and regulations that promote and shape a climate-friendly energy system. To capture the overarching impacts of the energy transformation, an integrated energy planning approach is required that combines a holistic, energy system-wide and long-term planning perspective. Long-term energy scenarios have a multiplicity of uses that can support planning for a climate friendly energy system. They can be used to open the dialogue needed among stakeholders to reach consensus, or to raise ambitions of roadmaps for long-term targets and identify short-term challenges when planning the clean energy transition. The boundaries of scenarios need to be expanded beyond the power sector to also integrate traditional fuels, industrial processes, LULUCF and other economy-wide impacts. Overall, there needs to be broader participation and stronger co-ordination across different stakeholders and government institutions involved in the energy scenario building and energy planning process. This should also contribute to setting long-term strategies that consider both energy and climate needs (coupled with the Sustainable Development Goals and the NDCs).

REGIONS PROVIDE THE LINK BETWEEN GLOBAL ASPIRATIONS AND LOCAL ACTION

While climate change is a global threat, transforming the energy sector involves different paths for different regions. Energy transition plans and priorities inevitably differ from country to country. Still, countries within a region also tend to face similar challenges, which can facilitate regional approaches. It may be easier for regions to co-operate and act together on regional energy transition goals than for countries to act alone. Energy transition actions at the regional and country levels must be aligned and consistent with global climate objectives. The inter-regional collaborations must also explicitly address issues of fairness and justice. Ramping up country and regional ambition and interlinking energy and climate is key for the energy transition. IRENA is committed to that effort and will be starting a series of regional investment forums to discuss opportunities with countries in those regions to accelerate the energy transformation. The results of this report will be used to facilitate discussions. A regional focus allows for better “action on the ground”.

Figure S.10 Different transition paths for different regions

Regional indicators including emissions, energy demand and electrification shares in the Transforming Energy Scenario

Transforming Energy Scenario (TES)

Regions	Emissions: Energy-related CO_2 (Gt CO_2/yr) 2017	2030	2050	Electrification in end-use consumption (% in TFEC) 2017	2030	2050
East Asia	11.2 Gt CO_2/yr	8.4 Gt CO_2/yr	2.2 Gt CO_2/yr	25%	37%	58%
European Union	3.4 Gt CO_2/yr	1.9 Gt CO_2/yr	0.6 Gt CO_2/yr	22%	30%	49%
Latin America and the Caribbean	1.2 Gt CO_2/yr	1.0 Gt CO_2/yr	0.6 Gt CO_2/yr	18%	26%	39%
Middle East and North Africa	2.5 Gt CO_2/yr	2.0 Gt CO_2/yr	1.1 Gt CO_2/yr	19%	20%	38%
North America	6.2 Gt CO_2/yr	3.7 Gt CO_2/yr	1.4 Gt CO_2/yr	20%	28%	52%
Oceania	0.4 Gt CO_2/yr	0.4 Gt CO_2/yr	0.1 Gt CO_2/yr	23%	22%	45%
Rest of Asia	3.5 Gt CO_2/yr	3.8 Gt CO_2/yr	2.0 Gt CO_2/yr	18%	26%	47%
Rest of Europe	2.0 Gt CO_2/yr	1.6 Gt CO_2/yr	0.7 Gt CO_2/yr	18%	23%	38%
Southeast Asia	1.4 Gt CO_2/yr	1.6 Gt CO_2/yr	0.8 Gt CO_2/yr	18%	20%	42%
Sub-Saharan Africa	0.8 Gt CO_2/yr	0.6 Gt CO_2/yr	0.3 Gt CO_2/yr	7%	23%	48%

Note: 2017 data based on IEA (2019b), Global Carbon Atlas (2019) and IRENA analysis.

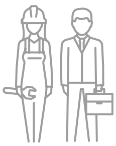
Renewable energy share in TPES (%) 2017	2030	2050	Renewable energy share in power generation (%) 2017	2030	2050	Clean energy investments (USD billion per year) 2016-2030	2016-2050
7%	27%	65%	23%	60%	90%	1120 USD bln	763 USD bln
15%	39%	71%	31%	55%	86%	424 USD bln	323 USD bln
30%	53%	73%	65%	85%	93%	154 USD bln	118 USD bln
1%	9%	26%	3%	27%	53%	198 USD bln	148 USD bln
10%	30%	67%	23%	60%	85%	609 USD bln	487 USD bln
10%	39%	85%	25%	66%	93%	37 USD bln	34 USD bln
8%	27%	58%	18%	52%	81%	420 USD bln	376 USD bln
6%	19%	54%	27%	42%	82%	244 USD bln	165 USD bln
13%	41%	75%	20%	53%	85%	143 USD bln	141 USD bln
7%	43%	89%	26%	67%	95%	95 USD bln	105 USD bln

TFEC = total final energy consumption; TPES = total primary energy supply.

GLOBAL SOCIO-ECONOMIC IMPACT

Renewable energy technologies lie at the heart of the energy transition. The transition roadmap outlined here points to a more sustainable energy system and lays the foundation for new patterns of socio-economic development. This report examines the transition's likely effects on employment and GDP, while also providing a composite indicator of human welfare. The analysis is based on a model that integrates energy, the economy and the environment. Its results can inform energy system planning, economic policy making, and other policies undertaken to ensure a just and inclusive energy transition at the global, regional and national levels.

JOBS



In the ambitious but achievable Transforming Energy Scenario, jobs in the overall energy sector – comprising transition-related technologies (renewable energy, energy efficiency, and power grids and energy flexibility), fossil fuels and nuclear power – could reach 100 million by 2050. This is 15% more than under the Planned Energy Scenario (which reflects current national commitments and plans) and 72% more than total energy employment at present. Underlying the total are significant changes in the composition of employment. New jobs in transition-related technologies and sectors are expected to outweigh job losses in fossil fuels and nuclear energy. In 2050, energy efficiency alone could employ 21 million people, and power grids and energy flexibility another 14.5 million – 21% and 14% more, respectively, than under the Planned Energy Scenario. By contrast, the 22 million jobs in fossil fuels in 2050 would be 27% fewer than in the Planned Energy Scenario.

Investment projected under the Transforming Energy Scenario would stimulate considerable job growth, most of this directly in renewables, where employment would rise to 42 million jobs by 2050. This is 64% more than expected under the Planned Energy Scenario and close to four times the number of jobs in the sector today. Solar photovoltaic (PV) would account for almost half of these jobs, followed by bioenergy and wind. Among segments of the renewable energy value chain, construction and installation jobs would dominate, accounting for 47% of the total. In terms of occupational profile, construction and factory workers, together with technicians, would hold a 77% share of total employment.

This expanded renewable energy workforce will require specific knowledge and skill sets. The labour market must be able to meet those needs, which would entail education, (re-)training and social policies, among other measures. Beyond the deployment of renewable energy technologies, other sectoral and economy-wide transition trends are sure to affect the evolution of employment in the broader energy sector.

The Transforming Energy Scenario would also achieve a net increase – close to 7 million – in the total number of jobs created economy-wide by 2050, 0.15% more than under the Planned Energy Scenario. The economy-wide employment figure reflects key assumptions and drivers, including not only investments, but also indirect and induced effects across many sectors of the economy, as well as changes in trade patterns. Notwithstanding the overall net job gain, reallocations of investment and changed consumption patterns would trigger job losses in some areas.

Maximising the job creation potential of the energy transition requires a solid understanding of future skill requirements and effective ways to facilitate the corresponding shifts in the labour force. Just and inclusive transition policies can limit labour market disruptions – *i.e.*, the job losses and misalignments that can be expected to occur during the energy transition. Targeted education and capacity-building policies must anticipate impending changes and nurture the diverse and growing labour force required by the transition.

GROSS DOMESTIC PRODUCT

Global GDP in 2050 would be 2.4% higher under the Transforming Energy Scenario than under the Planned Energy Scenario. The cumulative gain would be about USD 98 trillion, a finding shaped by several drivers in the global economy. Front-loaded investments would contribute most to GDP growth during the first years of the transition and retain a positive but relatively small impact thereafter. GDP gains can be explained in great part by changes in consumer spending in response to fiscal policy, as well as other indirect and induced factors. By comparison, trade would add only marginally more to global GDP gains under the Transforming Energy Scenario than under the Planned Energy Scenario, as global trade flows remain broadly balanced in both scenarios.

The cumulative gains in global GDP (USD 98 trillion) would greatly exceed the investment costs of transforming the energy system (USD 15 trillion). The world's GDP would grow by USD 367 per capita per year under the Transforming Energy Scenario, substantially greater than the additional per capita total investment (USD 54) needed to produce those gains. Increased investment and the prospects of economic growth and job creation could all help to obtain political buy-in. Still, the ultimate goal of the transition is to improve people's welfare through clean energy supply, economic and social development, and mitigation of climate change.

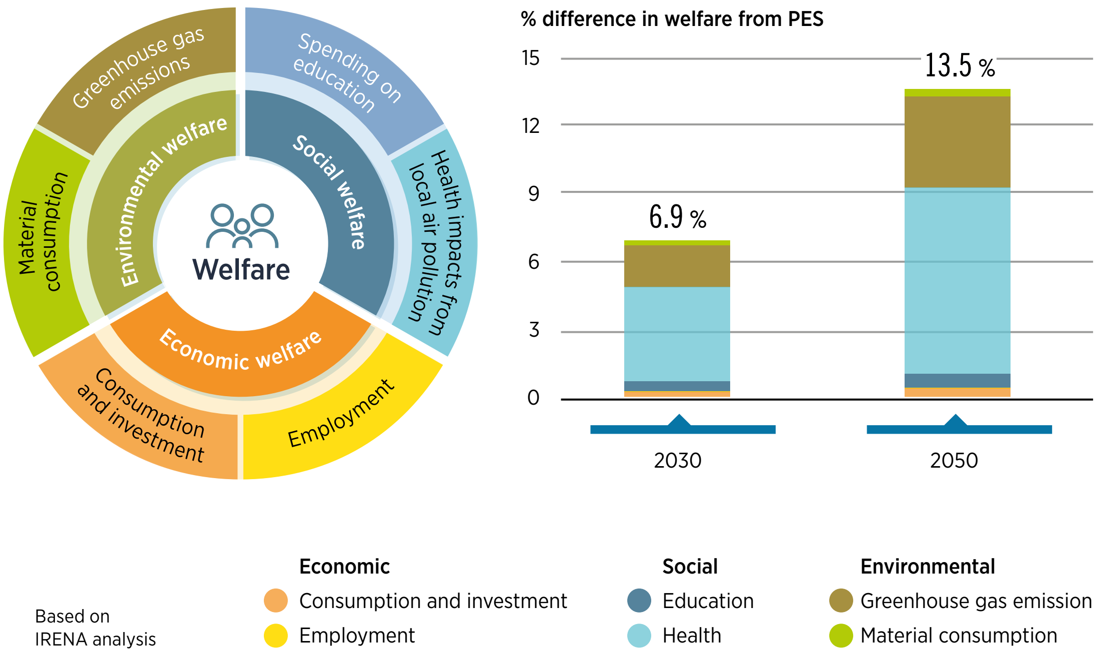
WELFARE

Welfare would improve faster and further under the Transforming Energy Scenario – with global welfare gains estimated at 13.5% by 2050 – than under the Planned Energy Scenario. The composite welfare indicator in the IRENA model reflects the multidimensional nature of human welfare, encompassing economic, social and environmental components (Figure S.11). The economic dimension is measured via household consumption and a composite of total investment and employment. The social dimension reflects spending on education and health. The environmental dimension entails greenhouse gas emissions and the consumption of materials. The bulk of the welfare gains under the Transforming Energy Scenario would take the form of social and environmental gains, reflecting significant health improvements from curbing air pollution and greenhouse gas emissions.

The energy transition would bring substantial socio-economic benefits at the global level. Yet at the country and regional levels, outcomes could vary widely. This is owing to variations in regional and country-specific socio-economic structures and their complex interactions with the energy system. The specific challenges and opportunities in each part of the world call for local solutions.

Figure S.11. Welfare gains: Influenced by health benefits and emission reduction

Global welfare indicator under the Transforming Energy Scenario in 2030 and 2050



Based on IRENA analysis

REGIONAL SOCIO-ECONOMIC IMPACT

Main report **Chapter 4**

The transition will occur in countries and regions at varying stages of development and with different economic structures. Differences include resource endowment, industrial productive capacity, industrial support policies, trade structures and domestic supply chains. All these factors determine the degree to which any economy can take advantage of the opportunities offered by the energy transition. Accordingly, results will vary among individual regions in terms of jobs, GDP and welfare.

The regional impacts of the transition, both in the energy sector as a whole and in its constituent parts, are sure to vary. Careful analysis of the likely outcomes will be required for conventional energy (fossil fuels and nuclear) and transition-related (renewables, energy efficiency, and system flexibility and grid enhancement) industries. The net impact of the Transforming Energy Scenario will depend on the current structure of the energy sector in each region, on regional energy sector roadmaps, and on regional trade patterns associated with transition-related equipment.

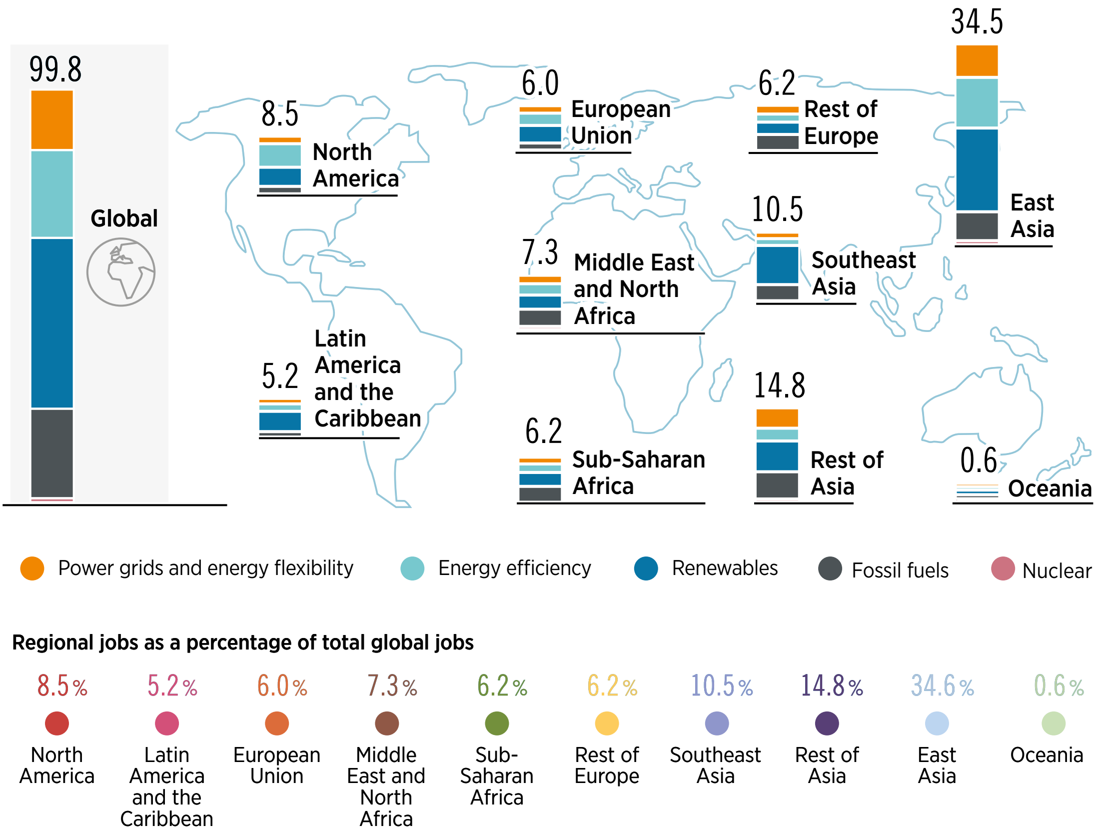
Differences in resource endowment, industrial productive capacity, industrial support policies, trade structures and domestic supply chains determine the degree to which any economy can take advantage of the opportunities offered by the energy transition

ENERGY SECTOR JOBS

The total number of energy sector jobs is expected to expand under the Transforming Energy Scenario to nearly 100 million (up from 58 million in 2017), but their spread will be uneven among regions. Asia dominates with a 60% share of all energy sector jobs in 2050 (Figure S.12). Compared with the Planned Energy Scenario, all regions gain jobs under the Transformed Energy Scenario. But Southeast Asia experiences the largest differential (81%), followed by Oceania (57%), Sub-Saharan Africa (36%) and North America (28%).

Figure S.12 A hundred million energy jobs: Regional distribution

Energy sector jobs in 2050 under the Transforming Energy Scenario, by region



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The number of jobs created in the overall energy sector will vary by technology and region. The jobs impacts in absolute numbers are largest in Asia and lowest in Oceania and Latin America. In East Asia and the Rest of Asia region, job losses are the highest of all, yet they are nonetheless surpassed by gains in transition-related technologies (Figure S.13).

Figure S.13 Energy sector job gains: Exceeding losses in every region

Difference in energy sector employment in 2050 between the Transforming Energy and Planned Energy scenarios, by region and sector

Based on IRENA analysis

TRANSITION-RELATED JOBS

Jobs intrinsically linked to the transition include those in renewable energy, energy efficiency, power grids and energy flexibility.

Under the Transforming Energy Scenario, **the employment share of transition-related technologies will rise against that of conventional technologies in all regions.** The transition-related share ranges from a high of 85% for North America and the European Union to a low of 60% for Sub-Saharan Africa and Rest of Europe (non-EU). Southeast Asia and Latin America will have the highest shares of jobs in ***renewable energy*** (83% and 72% respectively), while North America and the Middle East and North Africa (MENA) should fall at the lower range (40% and 45% respectively). In ***energy efficiency*** jobs, North America is far ahead of other regions, at 45% of its total energy sector jobs; the share is 29% in the European Union. Southeast Asia has the lowest share of energy efficiency jobs (7%), while the share in other regions lies between 10% and 25%. With respect to ***power grids and energy flexibility***, the share of jobs is highest in the Rest of Asia (22%) and the Rest of Europe (17%) and lowest in Southeast Asia (6%).

Employment gains can be realised in every region by 2050 in all transition-related technologies. In ***renewable energy***, the relative increase in the Transforming Energy Scenario over the Planned Energy Scenario ranges from more than 20% in East Asia and Latin America to 380% in Oceania. In ***energy efficiency***, regions would experience a relative gain ranging from 10% to 115%, with the Rest of Europe and the Rest of Asia regions faring best. In ***power grids and energy flexibility***, the gains will range from about 6% in the Rest of Europe, East Asia and the Rest of Asia to almost 65% in North America.

The regional distribution of renewable energy employment in 2050 varies widely under the Transforming Energy Scenario. The share of the world's renewable energy jobs is as high as 36% in East Asia but as small as 1% in Oceania, which largely reflects the size of populations, workforces and investments (Figure S.14). In terms of technology, solar will account for half of all renewables jobs in North America and in Asia, followed by Europe with 30%. By contrast, bioenergy is most prominent, with a share of over 60% of renewables jobs, in Latin America, Southeast Asia, Sub-Saharan Africa and the Rest of Europe. Wind is strongest in East Asia and the European Union, with about 25% of jobs; the figure is about 15% in North America and the MENA region. Hydro jobs account for 15% of all renewable energy jobs in the Rest of Asia and 10% in Latin America and the MENA region.

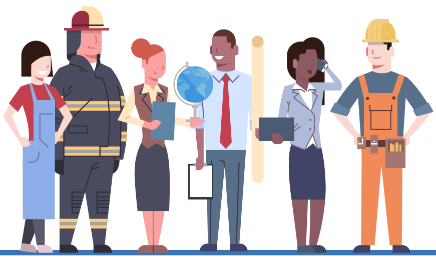
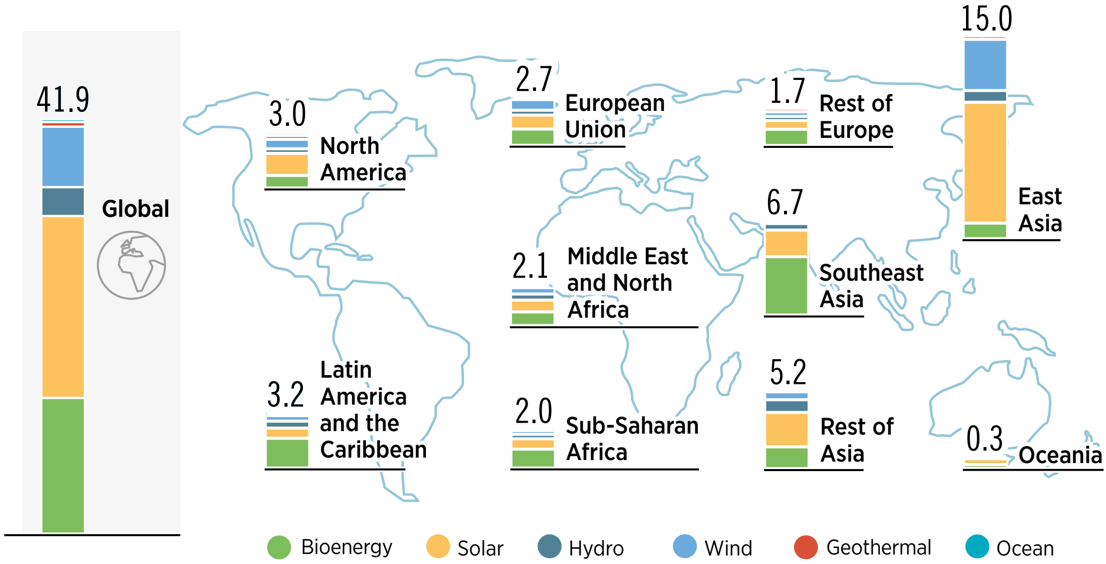
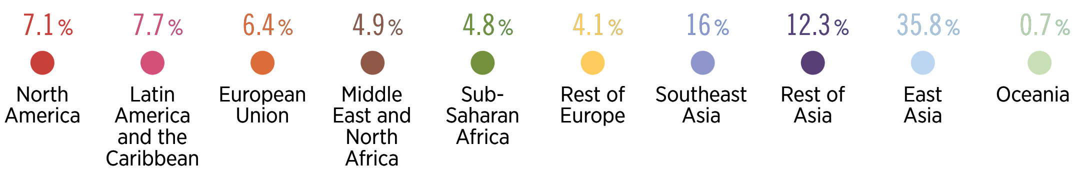


Figure S.14 An estimated 42 million jobs in renewables: Regional distribution

Renewable energy jobs in 2050 under the Transforming Energy Scenario, by region



Regional jobs as a percentage of total global jobs



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All regions gain more energy sector jobs than they lose as jobs in transition-related technologies outweigh the loss of jobs in the fossil-fuel sector

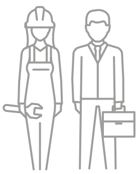
CONVENTIONAL ENERGY JOBS

In contrast to the gains for transition-related technologies, the Transforming Energy Scenario leads to lower projected employment in the conventional energy sector in all regions. For ***fossil fuels***, the largest declines, of around 40%, are projected for North America, East Asia and the European Union. The Rest of Asia follows with a roughly 30% decline, while Latin America and the MENA region would drop about 25% each. Fossil-fuel job losses concern not only exporters but also importers that have built up extensive infrastructure, distribution networks, assets and human know-how around these forms of energy. In ***nuclear energy***, all regions are set to lose jobs as well, with declines ranging from 20% in Latin America, East Asia and the Rest of Asia, to as much as 65% in Europe and North America.

Even as conventional energy employment shrinks overall, the share of conventional energy jobs remains high in some regions. Conventional energy jobs account for up to 40% of energy sector employment in Sub-Saharan Africa, the MENA region and the Rest of Europe compared with 10% to 15% in the European Union, the Americas and East Asia. The remaining conventional energy employment reflects a continuing degree of reliance on these sources.

As the energy transition accelerates, the job loss in conventional technologies becomes more pronounced. For the design of just transition policies that leave no one behind, detailed analysis will be needed to understand the structure of qualifications in the jobs lost and the composition of the labour force.

ECONOMY-WIDE EMPLOYMENT



Energy is an integral part of every economy, interacting with every other sector, affecting relative wages and generating income to be spent in other sectors. The embedded character of the energy sector within the wider socio-economic system, and the complex dynamics of the transition, will induce positive or negative effects in other economic sectors. In turn, other sectors may contribute favourably or adversely to transition challenges within the energy sector. A holistic, just transition policy framework is needed to bring about the best possible outcome.

Whether a region experiences growth or decline in economy-wide jobs depends on various factors, including energy transition roadmaps and regional socio-economic structures. The European Union and North America, respectively, are expected to gain 2.4% and 1% in economy-wide jobs in 2050 over the Planned Energy Scenario. These regional gains are significantly higher than the global average gain of 0.15%. All other regions gain less than 0.5% in economy-wide employment, and some even face a loss of jobs (MENA region, Rest of Europe, Latin America, Southeast Asia and the Rest of Asia). Sub-Saharan Africa shows no significant change.

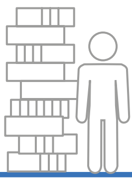
Despite new, transition-related job opportunities, labour market challenges are sure to arise in various sectors of the economy. The loss of jobs in the fossil-fuel sector is the most prominent example of these challenges, but other sectors may also be affected. In fact, the analysis indicates that across entire economies, some regions face the prospect of lower 2050 employment under the Transforming Energy Scenario than under the Planned Energy Scenario. At the economy-wide level, some regions, such as the European Union, North America and East Asia, experience a strong net positive benefit owing to their economies' ability to capitalise on indirect and induced effects of the energy transition. Sub-Saharan Africa and the Rest of Asia lack this ability, given their less diversified and weaker supply chain structures. Others, such as coal and hydrocarbon dependent regions, face a net negative outcome in comparison to the Planned Energy Scenario.

Structural realities may translate into different kinds of labour market misalignments of a temporal, spatial, educational or sectoral nature – a potential in any transition. The quantification of potential sectoral job misalignments, as revealed by the present socio-economic analysis, should inform policy making on the just transition. Because labour challenges are context-specific, a just transition will depend on context-specific policies in each region and country.

GROSS DOMESTIC PRODUCT

In the period 2019-2050, the average difference in GDP between the two scenarios amounts to 2% globally, but the gains in individual regions show considerable variation. The projected results range from a gain of almost 5% in the European Union to a loss of 0.5% in the MENA region. Regions scoring better than the global average include Southeast Asia and East Asia, while the Rest of Europe, North America, the Rest of Asia and Sub-Saharan Africa fall below the average. The MENA region and Oceania are the two exceptions that would experience less GDP growth under the Transforming Energy Scenario than under the Planned Energy Scenario.

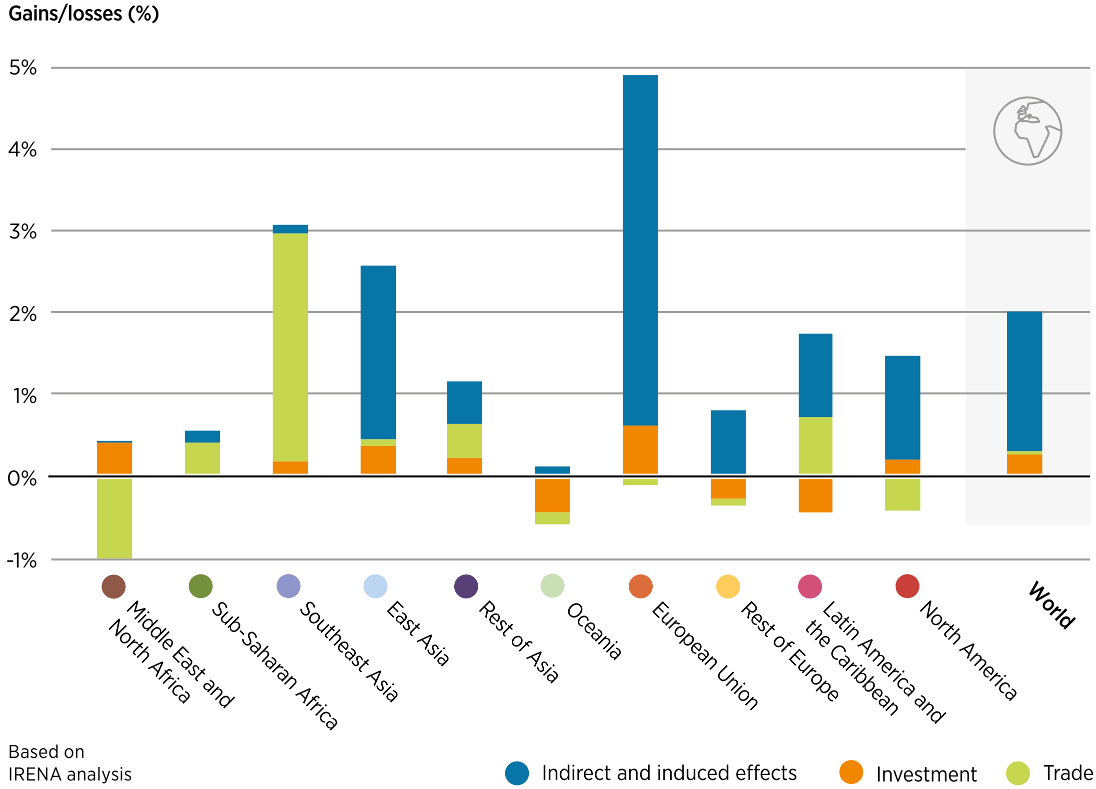
Trade plays a prominent role in shaping the future of some regional economies. The large GDP gains in Southeast Asia and Sub-Saharan Africa are attributable to a strong increase in net exports, whereas the MENA region faces the opposite dynamic, driven by the loss of hydrocarbon exports. The positive trade effect in Latin America and the Rest of Asia is quite pronounced; North America, by contrast, faces a drag from reductions in fossil-fuel trade and even more so trade in other goods and services (Figure S.15).



Whether a region experiences growth or decline in economy-wide jobs depends on various factors, including energy transition roadmaps and regional socio-economic structures

Figure S.15 Largest drivers of GDP gains: Transition effects and trade

Effect of three sets of drivers on the differences in regional GDP between the Transforming Energy and Planned Energy scenarios over the 2019-2050 period



Based on IRENA analysis

Investment levels are another important driver of the transition's regional socio-economic outcomes. At the global level, transition-related clean energy investments average USD 122 per capita per year. Among regions, the amounts vary widely, from about USD 50 per capita per year in Sub-Saharan Africa to more than USD 450 per capita per year in North America. Not only are the macroeconomic impacts consequently higher where investments are larger, but the multipliers in each economy play a significant role in determining the strength of investment effects.

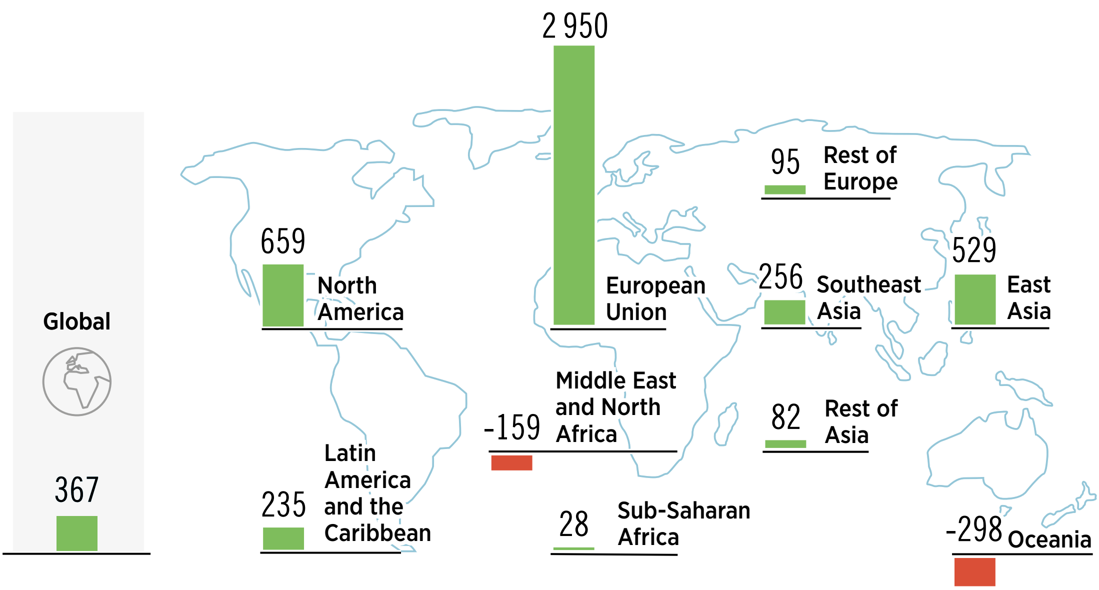
The presence of robust supply chains allows indirect and induced effects to contribute positively to the economy, especially if supported by appropriate fiscal policies. This is particularly the case in some of the major economic regions, such as the European Union, East Asia and North America. Additional employment is a key factor in triggering induced effects, as it leads to additional wage income, which has multiplier effects through increased consumer spending. Fiscal policies are most effective if they are based on a clear understanding of the local socio-economic context in a given region or country. But their successful implementation hinges on the presence of complex administrative infrastructure.

The diverging outcomes of the transition process can be attributed to different regional socio-economic starting points. This means that even if all regions had the same level of ambition and success in implementation, their results would be different. The underlying causes can be traced back to several country factors and structural realities: macroeconomic conditions, fossil fuel and other dependencies, institutional fabrics and capabilities, investment patterns and trade positions.

Under the Transforming Energy Scenario, the cumulative global GDP gains of USD 98 trillion by 2050 translate into an average of USD 367 per capita each year. The distribution of these gains is uneven across the regions. The European Union is expected to gain as much as USD 2 950 per capita per year, reflecting its strong socio-economic structures, but for most regions the gain is between USD 650 to about USD 100. Sub-Saharan Africa is projected to experience a modest increase of about USD 30, while the MENA region and Oceania would see a decline relative to the Planned Energy Scenario (Figure S.16). Variations in economic outcome contribute to the differences in the welfare estimates for these regions.

Figure S.16 Regional differences in GDP gains per capita

Cumulative GDP gains by region under the Transforming Energy Scenario compared with the Planned Energy Scenario (in USD, per person per year)



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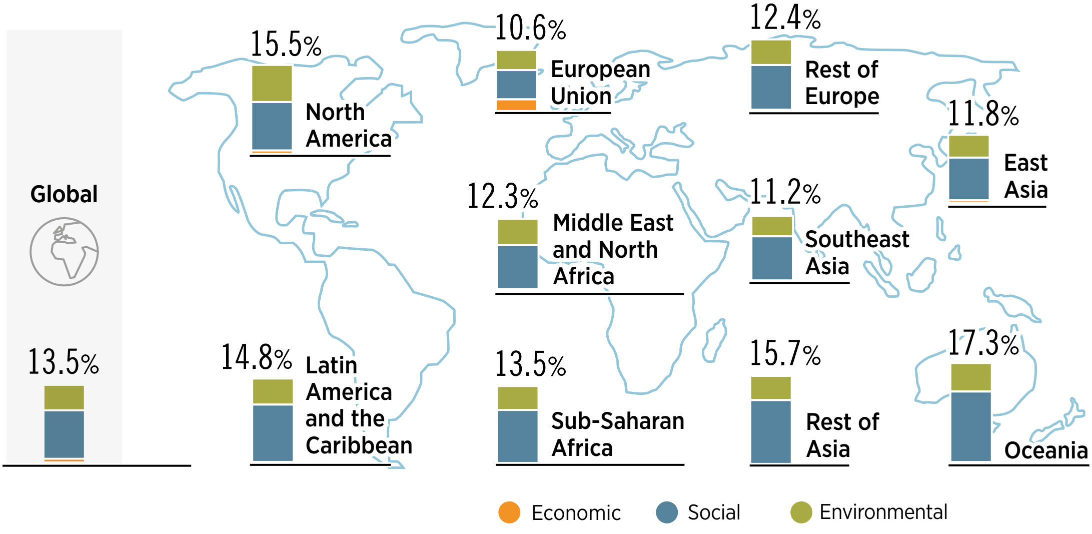
WELFARE

The transition would bring significant improvements in people's welfare in every region. Compared to the Planned Energy Scenario, the Transforming Energy Scenario strengthens the welfare index between 10% in the European Union and 17% in Oceania. The Rest of Asia, the Americas, and Sub-Saharan Africa fare slightly better than the global average, while the remaining regions score slightly lower.

Welfare gains are mostly due to progress in social and (secondarily) environmental indicators. Social indicators include two sub-components: health and education. On the health side, improvements due to reduced air pollution have the strongest effect across all regions, with people suffering most from air pollution achieving the greatest welfare gains. Among the two environmental sub-indicators, the mitigation of greenhouse gas emissions features more prominently than changes in the consumption of materials. Again, this is true across all regions. The economic indicator (composed of employment and consumption and investment) is most evident in the European Union and North America (Figure S.17).

Figure S.17 Regional-level welfare improvements driven by social and environmental gains

Composite welfare indicator in 2050 under the Transforming Energy Scenario, by region



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IMPLICATIONS

All regions of the world can expect to derive benefits from the energy transition, but thorough, granular analysis is needed to understand the reasons for regional differences. Individual regions will not gain equally in the transition-related sectors (renewables, energy efficiency, and power grids and energy flexibility), and they will face losses in the conventional energy sector to different degrees.

Regional outcomes will vary for GDP, employment and human welfare. With regard to jobs, the outcome for different regions will also diverge for the energy sector and its main components (transition-related and conventional energy) and with regard to the economy as a whole.

Differences in regional socio-economic outcomes can be traced back to contrasts in their structural conditions, industrial capacities and trade patterns, and the depth and diversity of domestic supply chains. Existing structures can be altered over time through policy ambition and far-sighted planning. Taking full advantage of the opportunities offered by the energy transition requires that interlinkages between the energy transition and the wider economy be analysed at sub-regional and national levels.

To achieve a successful transition, energy policies must be mainstreamed into economic, industrial, labour, educational and social policies. Cross-cutting and coherent policy making can deliver on climate and energy ambitions; put in place a mix of programmes, projects and initiatives to generate successful outcomes; and avoid or reduce potential misalignments in labour markets as the energy transition unfolds.

Unforeseen developments. The novel coronavirus (COVID-19), its impact on the global economy and the resulting fall in oil prices in early 2020 serve as reminders of how unforeseen factors can disrupt both actual trends and planned processes. These developments confirm the importance of close inter-connections between the energy system and the wider economy. Amid the complexities of the real world, deep-rooted structural dependencies will require persistent efforts to overcome.

Coronavirus is sure to affect the energy transition, too, threatening global supply chains in many sectors. Oil price volatility could have contradictory effects, in part because oil plays a marginal role in the power sector but is much more important in the transport sector, which accounts for half of total demand, and where without low-emission transport policies in place, an extended period of low oil prices may impact the speed of electric vehicle adoption. Conversely, oil price volatility may undermine the viability of unconventional oil and gas resources as well long-term contracts. The severity and duration of such impacts remain to be seen. Yet they will not change the path required to build a low-carbon society.

TOWARDS THE TRANSFORMATIVE DECARBONISATION OF SOCIETIES

Main report **Chapter 6**

Rapidly mounting climate concerns, rampant economic inequality and simmering social justice issues require a comprehensive global economic transformation. These challenges call for holistic solutions, with renewable energy playing a key role. A successful energy transition is central to the achievement of interconnected objectives, such as meeting climate goals, fostering economic development, creating jobs and promoting shared welfare.

The decarbonisation of the global economy in a relatively short time frame calls for unprecedented, large-scale policy interventions and massive resource mobilisation. The confluence of social justice, economic and climate issues has prompted calls for a global "Green New Deal" to bring about massive shifts in the world's energy system and economy, accompanied by measures to ensure a just transition for affected workers and communities through public interventions on an unprecedented scale. The key lies not just in a given set of policies but in the recognition that a transformative decarbonisation of societies is needed.

As countries and regions embark on their transformation pathways, their respective, different starting points reflect their various structural dependencies and the depth of their domestic supply chains. These factors, including dependencies on fossil fuels and other commodities, technologies and trade, will inevitably be reflected in the outcomes of the energy transition in 2050. Despite positive outcomes at the global level, the energy transition is likely to generate very different outcomes for individual regions and countries.

Fossil-fuel dependence is reflected in flows of finance and economic structures. Beyond export revenues for producers (as a share of their GDP or government budgets), dependence extends to the multiple facilities required for extracting, processing and distributing oil, gas and coal. This has implications for the sectors that provide supply chain inputs, and for institutions that educate and train the workforce. However, dependence is hardly limited to energy exporters. Importers, too, have built up extensive infrastructure, distribution networks, assets and human know-how around oil, gas and coal. Such forms of dependence may become a liability as the energy transition unfolds.

In addition to structural factors that need to be addressed, unforeseen developments may well influence the energy transition. The outbreak of the coronavirus is disrupting global supply chains in many sectors, including renewable energy. The oil price volatility observed in early 2020 has contradictory effects. It is unlikely to have a significant impact on renewables in the power sector (where oil plays a limited role) but could affect the speed of electrification in the transport sector. Oil price volatility could also undermine the viability of unconventional oil and gas (Box on "Unforeseen developments"). It is difficult to know how disruptive these developments will prove to be. While the short-term impacts loom large, they seem less likely to alter the long-term planning horizons for decarbonisation and sustainable development.

As countries around the world grapple with the challenge of transforming an energy system – and by extension a global economy – that relies on polluting conventional energy resources, notions of a "Green New Deal" are receiving growing attention in Europe and elsewhere. While this term is inspired by the New Deal of the 1930s, the name chosen for a given set of policy proposals is less important than recognising the need for a holistic approach to the energy transition that simultaneously addresses economic, social and ecological problems.

Market mechanisms alone will not bring about emissions reductions on the scale required in coming decades to transform the energy system and overcome structural dependencies. Alongside private sector financing, much stronger public-sector interventions and global collaborative efforts are needed to ensure the transition to a green, just and inclusive economy. Countries need to acquire or further develop their industrial capabilities and leverage them to take advantage of emerging opportunities in green technology development. Technological transitions, such as the rapid uptake of renewables and energy efficiency measures, can provide a temporary window of opportunity for lagging economies to catch up. Likewise, pre-existing productive capabilities, particularly in manufacturing sectors with high spillovers to the rest of the economy, can provide a promising basis for innovation in green technologies.

A successful energy transition will depend on a package of proactive, coherent public-sector interventions. In addition to measures to support technological innovation, bolstered by knowledge sharing and exchanges of best practices, such a package includes policies on the deployment and integration of renewables into energy distribution systems and end-use applications, as well as measures to ensure sufficient system flexibility as variable renewables (solar and wind) grow in importance. Further, enabling policies include industrial policies, labour-market interventions, educational and skills development, and social protection measures. Strategies for a just and inclusive transition aim to avoid or minimise dislocations for individuals, communities, countries and regions, thus ensuring broad benefits from the energy transition.

Success will depend on the strengthening of institutions, and also on broadening policy co-ordination and cohesion. At the national level, robust institutions can play a key role in accelerating the energy transition and driving change at the scale and magnitude needed. Co-operation is as important at the international level as it is within any country, not least because of tremendous variations in the ability of individual countries to marshal necessary resources, raise institutional capacities and develop technical know-how. A shared willingness to draw on lessons learned and best practices will benefit all and can herald a strengthened multilateralism for decarbonisation. This includes a rethinking of rules governing the global trade system with a view to supporting an ambitious and successful energy transition.

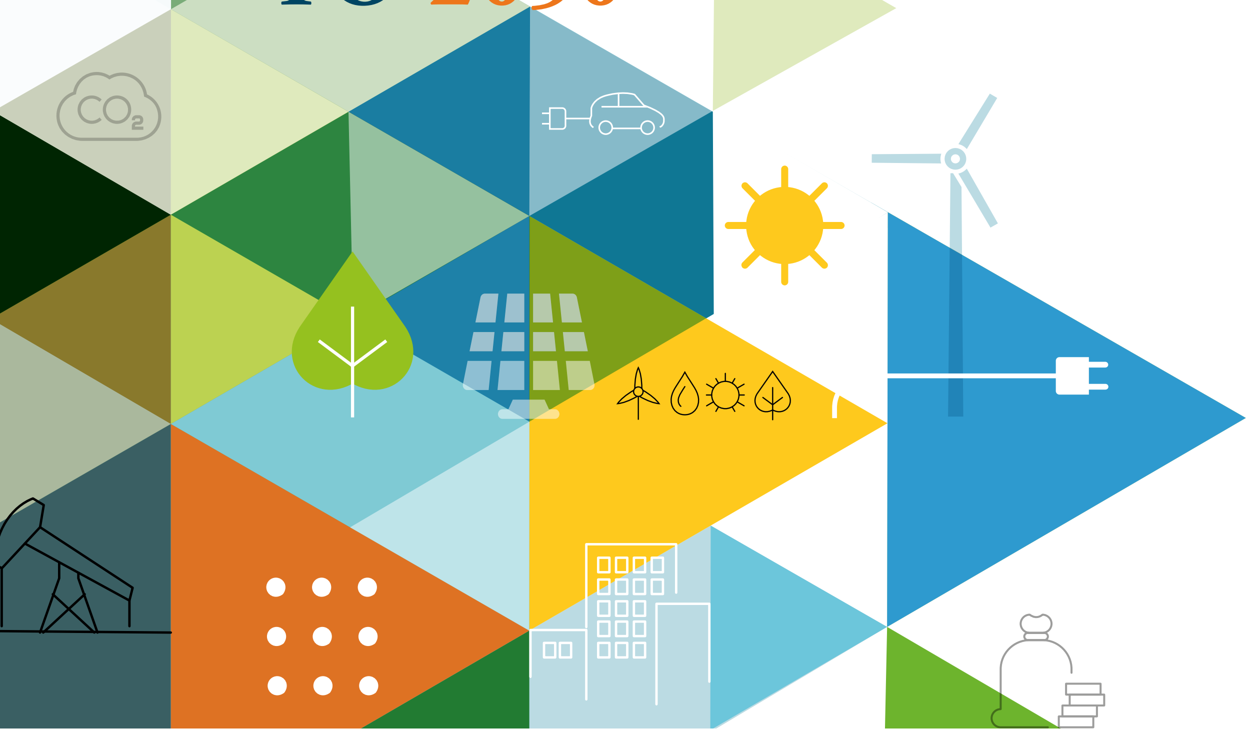
Mobilising resources on a massive scale is indispensable. At the international level, the Climate Investment Platform announced in September 2019 by the International Renewable Energy Agency, the United Nations Development Programme, the multi-partner Sustainable Energy for All initiative, and the Green Climate Fund aims to mobilise energy-transition investments on a scale commensurate with climate goals. Sub-regional investment forums, co-ordinated by IRENA, are intended to create enabling conditions, improve access to finance and assist developers in the preparation of bankable renewable energy projects.[1]

Ultimately, the success of the energy transition in mitigating the climate crisis will depend on the policies adopted, the speed of their implementation and the level of resources committed. In our interconnected world, international co-operation and solidarity are not only desirable, they are a vital condition for addressing climate change, economic inequality and social injustice. Moving forward, investment decisions should be evaluated on the extent to which they accelerate the shift towards an inclusive low-carbon economy. Anything short of that can seriously hamper the path towards a transformative decarbonisation of our societies.

[1] To learn more, see *https://irena.org/irenaforcip*.

01

THE ROADMAP TO 2050

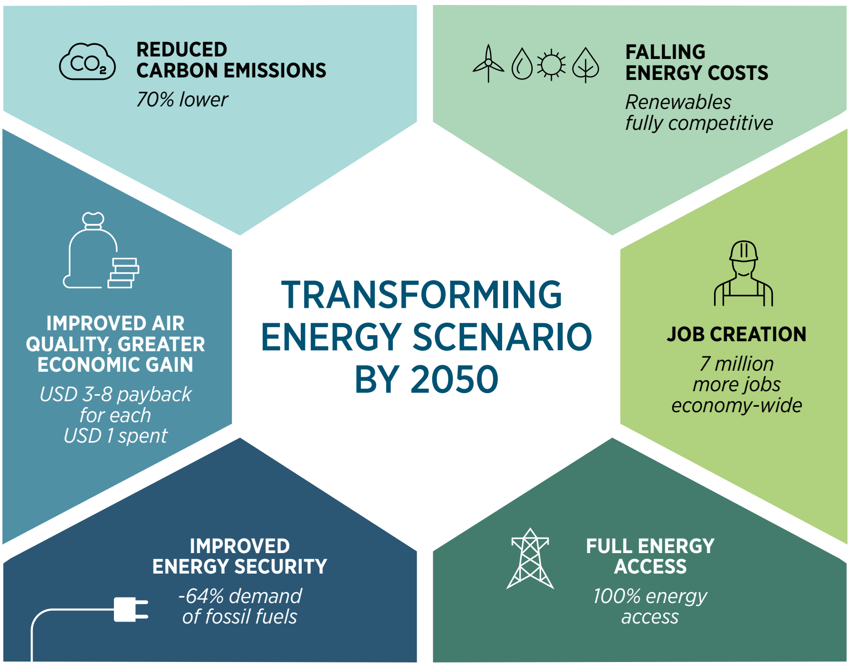


1.1 Drivers for the energy transformation

Climate change has become a major concern of this century. The urgent response to that concern is an energy transformation that swiftly reduces the carbon emissions that cause climate change. The Paris Agreement establishes a clear goal to limit the increase of global temperature to "well below" 2 degrees Celsius (°C), and ideally to 1.5 °C, compared to pre-industrial levels, by this century. To realise this climate target, a profound transformation of the global energy landscape is essential.

Rapidly shifting the world away from the consumption of fossil fuels and towards cleaner renewable forms of energy is critical to reach the climate goals agreed upon in Paris. Such a transformation is possible with the rapid replacement of conventional fossil fuel generation and uses with low-carbon technologies. Decarbonising the energy sector and reducing carbon emissions are the key objectives of the energy transformation roadmaps of the International Renewable Energy Agency (IRENA), which examine and provide an ambitious, yet technically and economically feasible, pathway for the deployment of low-carbon technology towards a more sustainable clean energy future. But the reduction of carbon emissions is not the only reason why the world should embrace the energy transformation. There are many other drivers behind it (Figure 1.1).

Figure 1.1 Pressing needs and attractive opportunities
Key drivers for the energy transformation



Rapid decline in costs for renewable energy: Global weighted average costs for electricity from all of the commercially available technologies for renewable power generation have kept falling in recent years. For example, the decline in the cost of electricity from utility-scale solar photovoltaic (PV) projects since 2010 has been remarkable. Between 2010 and 2019, the global weighted average levelised cost of electricity (LCOE) from solar PV fell 82%, reaching USD 68.4 per megawatt-hour (MWh), while the cost of electricity from onshore wind declined 45% to USD 52.8/MWh. In the last two years, solar corporate procurement jumped 44% worldwide, soaring to 5.4 gigawatts (GW) in 2018 and 9.6 GW in 2019 (Martin, 2020).

Between 2017 and 2018, nearly half of all solar PV auctions were held in South and East Asia and the Pacific, owing to high levels of solar irradiance and the falling cost of the technology. India alone allocated 17 GW of solar PV capacity auctions at an average price of USD 42.3/MWh. Likewise, China awarded 5 GW of solar PV at an average price of USD 64.6/MWh in a total of 10 auctions, and the Philippines received bids as low as USD 43.9/MWh in a 50 MW auction. IRENA'S database of power purchase agreement (PPA) and auction results suggests that the cost of solar PV generation will continue to fall in 2020.

Onshore wind auctions were most widely used in Europe, followed by South and East Asia and the Pacific. Offshore wind projects in Europe are now increasingly competitive with fossil fuel sources on a subsidy-free basis in wholesale electricity markets (*e.g.*, subsidy-free bids in Germany and the Netherlands). Germany alone auctioned more than 5 GW in seven rounds over 2017-2018 at an average price of EUR 51.65/MWh (USD 58.7/MWh).

In the United States, non-hydropower renewable energy resources such as solar PV and wind are expected to be the fastest-growing sources of electricity generation in the next two years. Biomass auctions were concentrated mainly in Europe and the Americas. Argentina awarded 143 MW of biomass at an average price of USD 107.5/MWh under the second round of the RenovAr programme. Concentrating solar power (CSP) was auctioned mainly in Central and Western Asia, specifically in the United Arab Emirates, where Dubai awarded 700 MW at a price of USD 73/MWh (IRENA, 2019h).

Air quality improvements: Air pollution is a major public health crisis, caused mainly by unregulated, inefficient and highly polluting energy sources (*e.g.*, fossil fuel combustion and chemical-related emissions). The switch to clean renewable energy sources, along with cost reductions and developments in electromobility, would improve the air quality in cities and bring greater prosperity by reducing ill health. It would also bring modern energy access to rural areas and increase productivity.

The benefits from reduced pollution and improved health could outweigh the overall system costs of renewables. The total savings in improved health, reduced subsidies and lower impacts of climate change would be worth as much as USD 160 trillion cumulatively over a 30-year period.

Thus, every dollar spent in transforming the global energy system provides a payoff of at least USD 5, and potentially more than USD 7, depending on how externalities are valued.

Reduction of carbon emissions and climate change impacts: Shifting away from fossil fuel use to renewable sources not only reduces carbon emissions, it would also reduce the impacts of climate change and improve conditions for society and business.

Universalisation of energy access: Transforming the global energy system would help lead to clean energy access for everyone. The current lack of energy access for millions of people is a cause of great inequality. Renewable energy technologies can be applied to rural areas where the grid has yet to reach, bringing rural electrification, community energy initiatives and distributed energy resources that can greatly improve people's lives and stimulate local economies.

Enhancement of energy security: For countries heavily dependent on imported fossil fuels, energy security is a significant issue. Renewables can provide a more secure alternative to fossil fuels by increasing the diversity of energy sources through local generation, thus contributing to the flexibility of the system and improving resistance to shocks.

Socio-economic benefits: Transforming the global energy system would also bring large socio-economic benefits, which are crucial to influencing any political decision. The transition process itself will bring about profound structural changes in labour markets, resulting in four types of job effects: job creation, elimination, substitution and transformation (IRENA, 2020a). The development of a local renewable energy industry has the potential to create jobs that can be filled by people of all genders and from all disciplines and backgrounds. Should local industries not be developed, countries with energy security problems would just move from importing fossil fuels to importing renewable energy equipment.

On the other hand, some jobs will become redundant, specifically in fossil fuel production but also in other sectors such as conventional automobiles (as electrification of transport takes place). Some of these jobs will be lost, but others could be saved through re-orientation measures. Shifting to a renewable-powered future also allows for retaining existing expertise from the fossil fuel industry, particularly for renewable industries such as offshore wind. For instance, the expertise of workers and technicians in building support structures for offshore oil and gas sites could potentially be used to build foundations and substations for offshore wind turbines (IRENA, 2019e).

The energy transformation would boost gross domestic product (GDP) by 2.5% and total employment by 0.2% globally by 2050. In addition, it would bring broader social and environmental benefits.

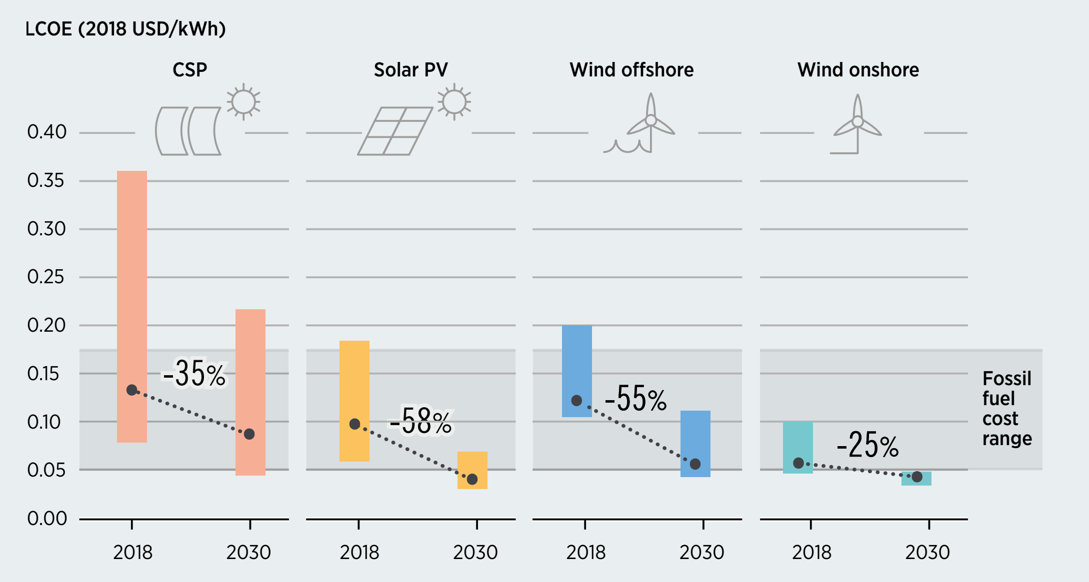
Box 1.1 RENEWABLE POWER GENERATION COSTS CONTINUE TO DECLINE

In most parts of the world today, renewables have become the lowest-cost source of new power generation. As costs continue to fall for solar and wind technologies, this will be true in a growing number of countries.

Data from the IRENA Renewable Cost Database show that since 2010, the global weighted average LCOEs from bioenergy, geothermal, hydropower, and onshore and offshore wind projects have all been within the range of fossil fuel-fired power generation costs, while for onshore wind, solar PV and CSP, costs continue to decline rapidly (IRENA, 2019i). Between 2012 and 2018, the LCOE of solar PV fell by 77%, CSP by 46%, onshore wind by 35% and offshore wind by 20%. Costs are expected to continue to decline for solar and wind power technologies to 2030 (Figure 1.2).

- **CSP: By 2030, the central LCOE value of CSP plants in G20 countries is likely to decline by 35% to USD 0.086 per kilowatt-hour (kWh) from a central estimate of USD 0.132/kWh in 2018.** The range of CSP LCOE estimates is also expected to narrow from between USD 0.077/kWh and USD 0.357/kWh to between USD 0.044/kWh and USD 0.214/kWh. Cost reduction drivers vary according to the specific type of technology. For example, parabolic trough systems can be expected to benefit from a step-change reduction related to the switch to molten salt as a heat

Figure 1.2 Solar and wind power: Expected cost reductions until 2030
LCOE development of CSP, solar PV, offshore and offshore wind technologies (G20 country averages), 2018-2030



Based on preliminary results from IRENA (forthcoming a) transfer fluid. This switch simplifies the plant layout, improves power block efficiency and reduces the cost of storage. In the case of solar tower systems, a more evolutionary approach from current state-of-the-art technological features is more likely that does not involve major general plant design modifications.

- **Onshore wind: Onshore wind is expected to see a decline of 25% between 2018 and 2030**, as the continued shift to larger wind turbines with higher hub heights and swept areas improves the capacity factor for this resource. Installed cost reductions provide an important contribution as well, as increases in the scale of deployment and manufacturing process improvements continue the historical trend towards lower costs. Innovations in operation and maintenance (O&M), including real-time data and predictive maintenance and the synergies from the management of large portfolios of turbines, also yield more efficient and timely operations.

- **Solar PV: The global weighted average LCOE for solar PV can be expected to continue its downward trend to reach USD 0.040/kWh by 2030 (a 58% reduction from 2018).** This decline will be driven by continued improvements in module efficiency levels, driven by a market shift towards increased dominance of advanced cell architecture such as the PERC (passivated emitter rear contact) cell technology in the period towards 2025. Over the longer term, newer architectures with even higher efficiency levels can be expected to drive further improvements.

In terms of cost components along the PV value chain, the ingot/wafer process cost reductions will be the most significant; they will be driven by polysilicon cost reductions, lower utilisation due to decreased kerf losses and manufacturing optimisation. At the cell manufacturing level, diamond wire and silver paste costs will continue to decline. Cost reductions for PV glass backsheet and encapsulant components are likely to also contribute to cheaper module assembly to 2030. An important market shift towards higher adoption of bifacial cells and modules, driven by the prevalence of the PERC architecture and its compatibility with that technology, can also be expected.

- **Offshore wind: Offshore wind is becoming competitive with other renewable energy technologies with improvements in the full life cycle of processes** (*i.e.*, from development down to O&M). The technology is improving, with larger turbines and higher turbine ratings (with up to 20 MW turbines expected to be used for projects in 2030). As a result, capacity factors are increasing, boosting energy yields and reducing total installed and O&M costs. Furthermore, competitiveness and LCOE reductions have been driven by the recent projects (since 2017) as lower auction prices and zero subsidy projects have increased competitive pressures (including consolidation) across the supply chain. The increased deployments and growing maturity of offshore wind markets in Europe and China between 2010 and 2019 have also reduced risks and uncertainty for investors. That has led to increased interest in the offshore wind sector and has reduced the costs of financing.

Considering historical LCOE trends (where technology trends and market drivers have been investigated and modelled) and PPA prices for projects being deployed up to 2030, **IRENA anticipates a central LCOE estimate of USD 0.054/kWh in 2030 – an almost 55% drop from the 2018 LCOE of USD 0.115/kWh**. The LCOE range in 2030 is wider with a more aggressive expectation for average LCOE in established offshore wind markets (*e.g.*, the United Kingdom (UK), Germany and China) of USD 0.039/kWh and an average expectation in newer markets (*e.g.*, Turkey and Japan) close to the 2018 weighted average, at USD 0.110/kWh.

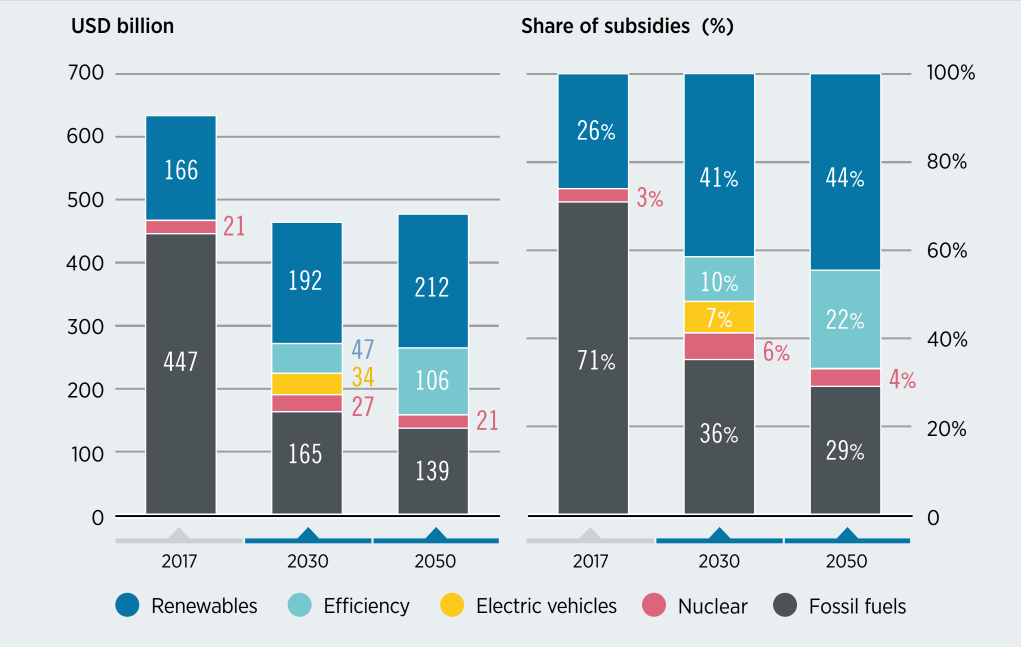
Box 1.2 ENERGY SUBSIDIES IN THE ENERGY TRANSFORMATION

As countries examine their plans in Nationally Determined Contributions (NDCs) under the Paris Agreement, significant attention is being paid to minimise the costs of the transition. However, ignoring the health and environmental costs of incumbent resources can result in sub-optimal investment decisions in the market and by policy makers. One area that deserves more attention in this debate is the size and impact of environmentally harmful subsidies to fossil fuels.

For virtually all of the modern era of energy usage, the energy sector has operated with a range of subsidies that have, to a greater or lesser extent, distorted market functioning (indeed, the sector has often actively sought these subsidies). In many cases, what policy makers or industries considered temporary subsidies – both well intentioned and egregious ones alike – have persisted for decades, as industry has actively sought to ensure their continuation. In some instances, industry has even actively framed the debate to exclude such policies from consideration, on the basis that they are not subsidies.

Figure 1.3 Energy subsidies: Overall reduction in the Transforming Energy Scenario

Total direct energy sector subsidies by fuel/source, 2017, 2030 and 2050 in the Transforming Energy Scenario



Based on IRENA (forthcoming b)

IRENA has estimated the direct subsidies to fossil fuels (*i.e.*, excluding externalities) at USD 447 billion in 2017 (IRENA, forthcoming b) based on data from the Organisation for Economic Co-operation and Development (OECD) and the International Energy Agency (IEA) (Figure 1.3). Meanwhile, the indirect subsidies to fossil fuels from underpricing of their negative externalities (*e.g.*, health costs from local pollution and climate change) were an estimated USD 2 630 billion in 2017.

Subsidies to fossil fuels are especially damaging to environment, because they exacerbate the existing underpricing of fossil fuels that typically do not pay the full cost for their negative externalities (*e.g.*, health costs from local pollution). Environmentally harmful subsidies for fossi fuels are around 19 times larger than support to renewables, which was around USD 166 billion in 2017. The order of magnitude of this problem is significant, and these indirect subsidies are estimated to be 19 times higher than those to renewables in 2017. Environmentally friendly support schemes to renewables, energy efficiency and other clean energy sources that lead to the displacement of fossil fuels when the negative externalities of fossil fuels from air pollution and climate costs remain underpriced, therefore help improve the economic efficiency of the sector, by helping correct for market failure. They do this by shifting energy generation and use towards technologies that reduce the negative externalities of fossil fuels. In 2017, subsidies for renewables were estimated at USD 166 billion, with around USD 38 billion for transport and USD 128 billion for power generation.

The evolution of total energy sector subsidies to 2050, assuming the virtual elimination of existing fossil fuel subsidies (by 2050 almost all the subsidies to fossil fuels derive from carbon capture and storage) and the increased deployment of renewables and energy efficiency, would result in a decline in total annual subsidies to the energy sector between 2017 and 2050. **The switch from environmentally harmful subsidies for fossil fuels to environmentally friendly ones would result in a 25% decline in total direct energy sector subsidies to USD 475 billion between 2017 and 2050, which is around 45% lower than they would have been in the Planned Energy Scenario in 2050.**

1.2 A widening gap between reality and what is needed

To set the world on a pathway towards meeting the aims of the Paris Agreement, energy-related carbon dioxide (CO_2) emissions need to be reduced by a minimum of 3.8% per year from now until 2050, with continued reductions thereafter. However, trends over the past five years show annual growth in CO_2 emissions of 1.3%. If this pace were maintained, the planet's carbon budget would be largely exhausted by 2030, setting the planet on track for a temperature increase of more than 3°C above pre-industrial levels. This case cannot be considered as a climate-compatible scenario, as many governments, by signing the Paris Agreement in 2015, committed to reducing their emissions.

Figure 1.4 shows the possible paths of annual energy-related CO_2 emissions and reductions as per three scenarios: the Baseline Energy Scenario (BES) (indicated by the orange line); the Planned Energy Scenario (PES) (indicated by the yellow line); and IRENA's energy transformation pathway – the Transforming Energy Scenario (TES) (indicated by the blue line).

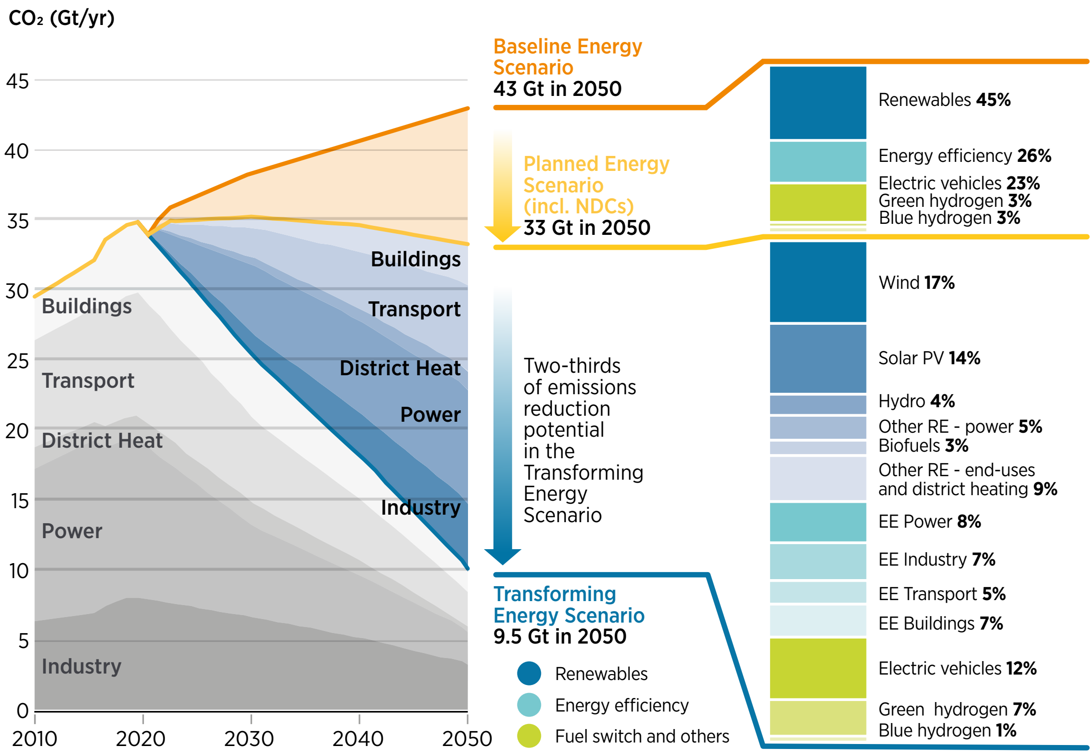
In the Baseline Energy Scenario, which does not necessarily imply the fulfilment of all plans and pledges of countries and considers only the policies in place around the time of the Paris Agreement (2015), energy-related emissions are expected to increase at a compound annual rate of 0.7% per year to 43 gigatonnes (Gt) by 2050 (up from 34 Gt in 2019), resulting in a likely temperature rise of 3 °C or more by the end of the century. However, several countries have made efforts in the last three years to implement policies and revise their targets in line with higher deployment of clean energy technology. Most of the efforts and ambition are oriented towards increasing renewable power generation capacities, followed by energy efficiency improvement targets and a subsequent rise in electrified transport and heat applications.

If the plans and pledges of countries are met as reflected in the Planned Energy Scenario, then energy-related CO_2 emissions are expected to increase each year until 2030, before dipping slightly by 2050 to just below today's level. However, to limit the global temperature rise to well below 2 °C and towards 1.5 °C as per the Paris Agreement targets, annual energy-related CO_2 emissions would need to fall more than 70% from now until 2050. In absolute terms, emissions would be reduced from 34 Gt today to below 10 Gt in 2050. A large-scale shift to renewable energy and electrification measures could deliver three-quarters of the needed reductions (electrification and renewables contributing to an emissions mitigation potential of 75%), or as much as 90% with ramped up energy efficiency measures.

To achieve such levels of emissions reductions, an acceleration is needed across a spectrum of sectors and technologies, ranging from rapid deployment of renewable power generation capacities such as wind, solar PV, etc., to deeper electrification of the end-uses of transport (*e.g.*, electric vehicles, EVs) and heat (*e.g.*, heat pumps) powered by renewables, direct renewable use (*e.g.*, solar thermal, biomass), energy efficiency (*e.g.*, thermal insulation of buildings, process improvement) and infrastructure investment (*e.g.*, power grids, flexibility measures such as storage).

IRENA's Transforming Energy Scenario outlines a climate-friendly pathway with energy-related CO_2 emissions reductions of 70% by 2050 compared to current levels, with 9.5 Gt of remaining energy-related CO_2 emissions by mid-century (Figure 1.4). Of the remaining 9.5 Gt of energy-related CO_2 emissions in 2050, just under one-quarter is emitted for both electricity generation and transport, one-third in industry, 5% in buildings and the remaining 15% in other sectors (agriculture and

Figure 1.4 Renewables, energy efficiency, electric vehicles and hydrogen can provide bulk of necessary emissions reductions by 2050
Annual energy-related CO_2 emissions in the Baseline Energy Scenario, the Planned Energy Scenario and the Transforming Energy Scenario, and mitigation contributions by technology in the three scenarios, 2010-2050

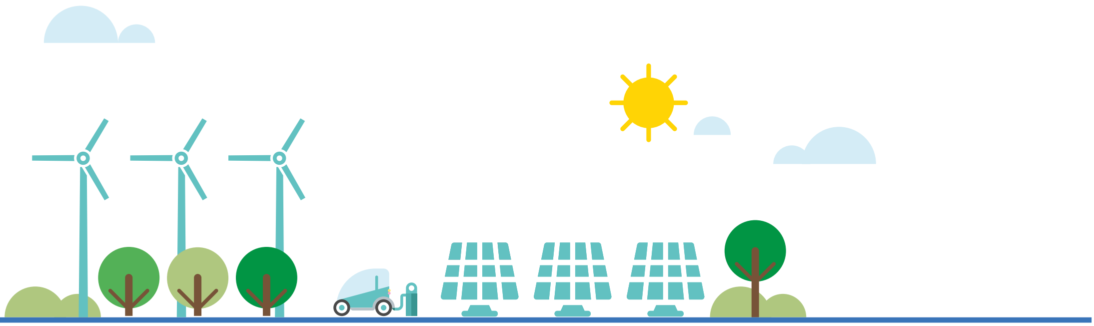


Note: The Transforming Energy Scenario includes 250 Mt/year in 2050 of carbon capture, utilisation and storage for natural gas-based hydrogen production (blue hydrogen). RE = renewable energy; EE = energy efficiency.
Based on IRENA analysis

district energy). The Transforming Energy Scenario is focused on energy-related CO_2 emissions reductions, which make up around two-thirds of global greenhouse gas emissions.

Beyond 2050, further efforts will also be needed, and emissions will need to fall to zero. The solutions needed to reduce the remaining 9.5 Gt of energy-related CO_2 emissions and 10.4 Gt of energy and process-related CO_2 emissions within that decade have yet to be fully analysed, although some solutions are in sight. In the transport sector, freight, air and shipping could be decarbonised further through a mix of electrification, biofuels, carbon-neutral synthetic fuels and hydrogen. In the industry sector, synthetic materials from biomass carbon and CO_2 could be used to replace petrochemical products. Zero-carbon steel and chemical industries would need to be achieved, through a combination of a circular economy, and hydrogen and biomass feedstocks. Most buildings would need to be zero energy through high efficiency and building-integrated renewables. Smart and sustainable city and infrastructure planning would need to become ubiquitous.

Chapter 5 of this report further explores IRENA's Deeper Decarbonisation Perspective (DDP) to reduce the Transforming Energy Scenario emissions to zero in the 2050-2060 time frame.

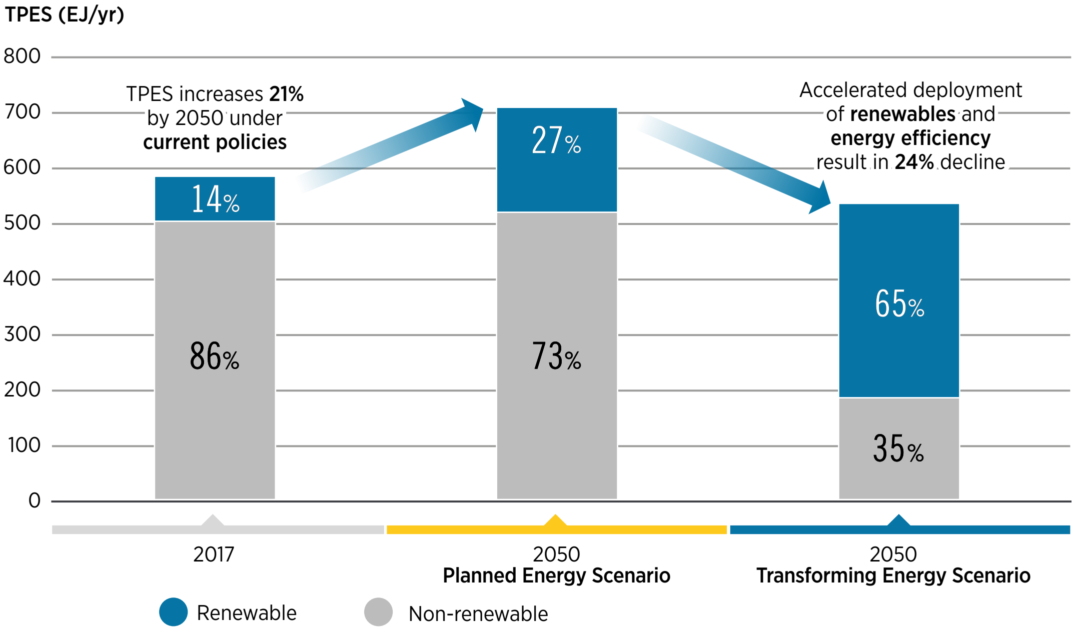


1.3 An ambitious and yet achievable climate-resilient transformative pathway to 2050: What does the transformation entail?

The transition to increasingly electrified forms of transport and heat, when combined with increases in renewable power generation, would deliver around 60% of the energy-related CO_2 emissions reductions needed by 2050. If additional reductions from the direct use of renewables are considered, the share increases to 75%. When adding energy efficiency, the share increases to over 90% of the energy-related CO_2 emissions reductions needed to set the world on a pathway to meeting the Paris Agreement targets.

The total share of renewable energy would need to rise from around 14% of total primary energy supply (TPES) in 2017 to around 65% in 2050. Under the Planned Energy Scenario, this share increases to only 27%, while under the Transforming Energy Scenario it increases to 65% (Figure 1.5). The renewable energy mix would change, with the share of renewables from bioenergy decreasing from two-thirds to one-third, and with a much higher share of solar- and wind-based energy in the Transforming Energy Scenario in 2050. TPES would also have to fall slightly below 2017 levels, despite significant population and economic growth.

Figure 1.5 To meet agreed global climate goals, renewables would need to provide two-thirds of the world's energy supply
Total primary energy supply, renewable and non-renewable share, for the Planned Energy Scenario and the Transforming Energy Scenario, 2017, 2050



Note: PES and TES (IRENA), 2017 values based on IEA (2019b)

In the period from 2010 to 2017, global primary energy demand grew 1.1% per year. In the Planned Energy Scenario, this is reduced to 0.6% per year to 2050, whereas in the Transforming Energy Scenario, the energy demand growth turns negative and results in a decline of 0.2% per year to 2050 (Figure 1.5).

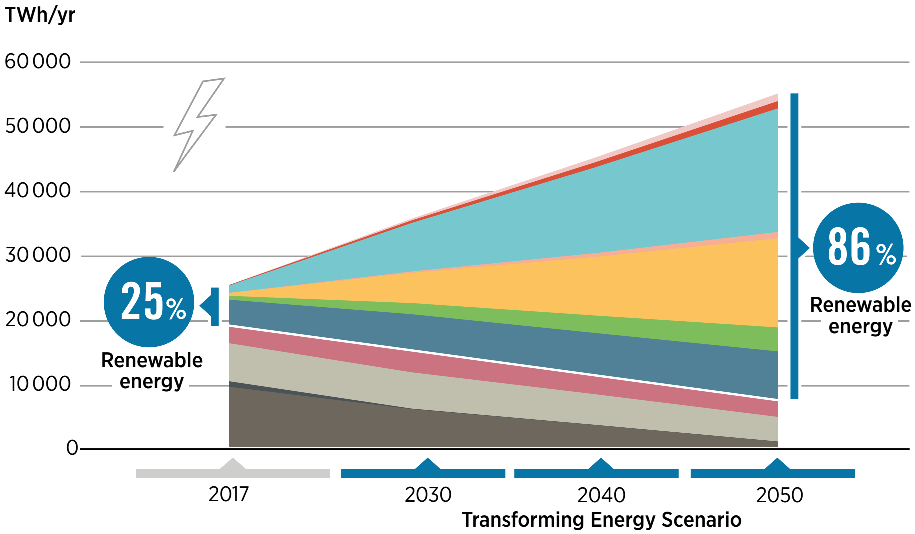
Scaling up electricity from renewables is crucial for the decarbonisation of the world's energy system. The most important synergy of the global energy transformation comes from the combination of increasing low-cost renewable power technologies and the wider adoption of electricity for end-use applications in transport and heat and hydrogen production. To deliver the energy transition at the pace and scale needed would require almost complete decarbonisation of the electricity sector by 2050. The Transforming Energy Scenario sets a pathway to achieve an 86% share for renewables in the power generation mix by 2050 (Figure 1.6). On the end-use side, the share of electricity in final energy consumption would increase from just 20% today to almost 50% by 2050. The share of electricity consumed in industry and buildings would double. In transport, it would increase from just 1% today to over 40% by 2050.

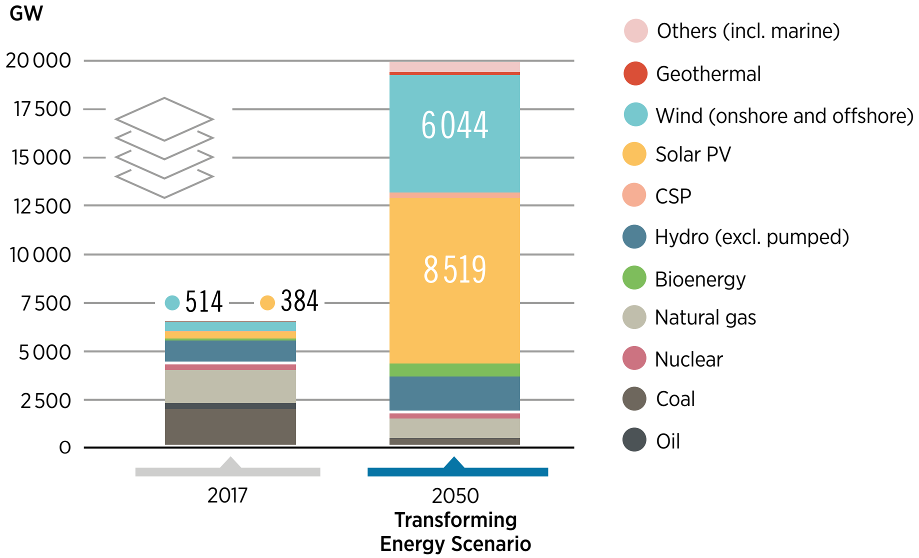
Solar PV and wind energy would lead the way in the transformation of the global electricity sector. Wind power would be a major electricity generation source, supplying more than one-third of total electricity demand. Solar PV power would follow, supplying 25% of total electricity demand (Figure 1.6), which would represent more than a 10-fold rise in solar PV's share of the generation mix by 2050 compared to 2017 levels. In the context of total installed capacity by 2050, much greater capacity expansion would be needed for solar PV (8 519 GW) as compared to wind (6 044 GW).

Hydropower can bring important synergies to an energy system of the future. For example, hydropower will play an important role in helping to integrate higher shares of variable renewable energy (VRE). In the Transforming Energy Scenario, hydropower capacity would increase by two-thirds to 2 147 GW by 2050 compared to current levels. In other words, around 850 GW of new installed capacity is required in the next 30 years. Of that, pumped storage would need to more than double to 325 GW, providing storage and energy flexibility. In addition to the new capacity, an estimated more than 600 GW of the current aging hydropower fleet will require refurbishment. That offers a timely opportunity to modernise hydropower to provide greater flexibility to support the variable sectors.

Hydropower also can play the additional roles of regulating river flows and reducing flooding. Increasing hydropower capacity does not entail only building new dams; options also exist to upgrade turbines and systems in existing plants and to electrify non-power dams. For new hydropower plants, planners need to consider local environmental impacts and to involve discussion with communities in the impacted areas. Hydropower plants will need operational changes that reflect changing power system needs, including faster and more frequent ramping, and planning practices that include evaluating the impacts of climate change on water supply and reservoir storage requirements. Due to longer planning cycles for hydropower dams, policy makers and planners would need to start thinking now about new projects. With enabling policies, market conditions, common frameworks to scale investments and well-prepared projects, hydropower will be one of the key technologies in coming decades.

Figure 1.6 Solar, wind and other renewable power generation until 2050
Breakdown of electricity generation and total installed capacity by source, 2017-2050





Note: PES and TES (IRENA),
2017 values based on IEA (2019b)

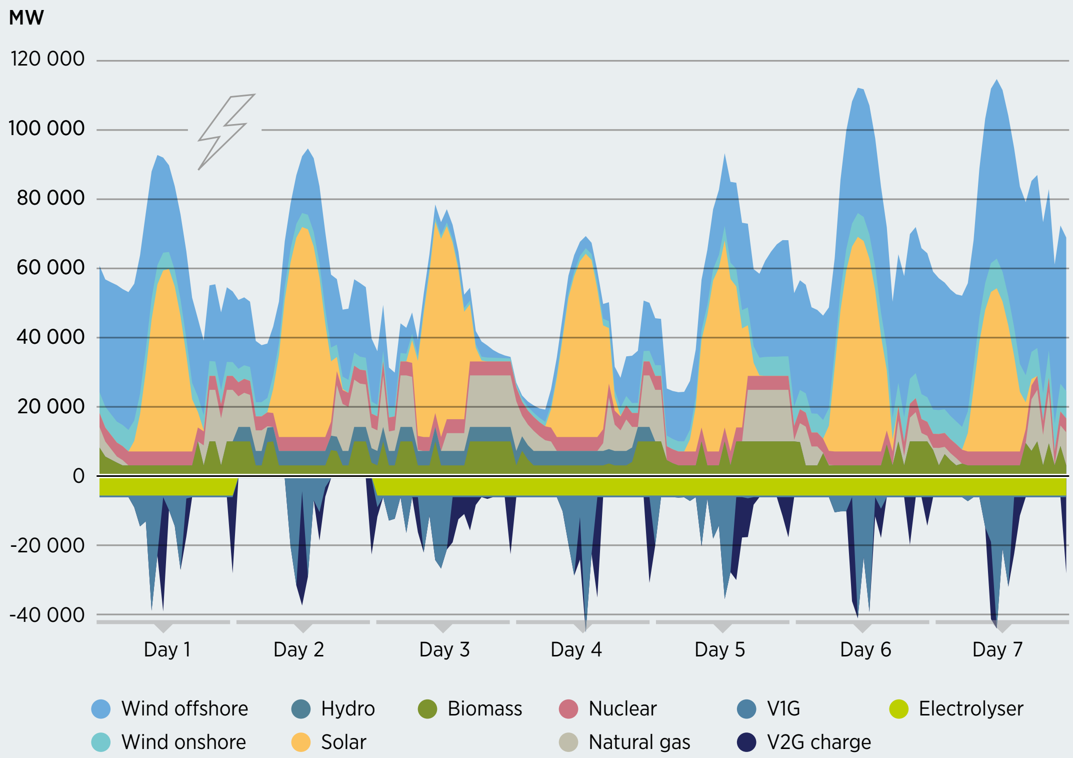
Notes: CSP = concentrating solar power;
TWh = terawatt-hour.

Box 1.3 OVERVIEW OF POWER SYSTEM FLEXIBILITY IN THE ENERGY TRANSFORMATION

A dispatch of the power system considered in the Transforming Energy Scenario was simulated for the year 2050 to further analyse the operation of the global power system developed by IRENA and to provide insights for the 2050 power system based on IRENA's energy scenarios.

Hourly dispatch of the global system was analysed for the whole world (at the national level for G20 countries, and otherwise regionally in line with the geographic disaggregation of the present report), along with national/regional renewable resource and demand profiles as well as unit commitment and dispatch constraints of generators such as minimum stable levels and ramping speed. This makes it possible to explore how such a system would work in terms of unit cycling, system ramping, and curtailment of VRE, and to assess how the different flexibility resources across the power system contribute to the operation of the system, as illustrated in Figure 1.7.

Figure 1.7 Hourly electricity dispatch in 2050: No major system flexibility issues
One-week dispatch of the UK power systems showing how select technologies balance demand and supply with large shares of solar and wind in 2050



Based on IRENA analysis

The analysis revealed that there are no macroscopic flexibility issues that lead to significant unserved energy in the power system in any country or region, and that curtailments of variable renewable wind and solar power are limited. While such findings are encouraging, they must be considered within the limitations of modelling that assumes no transmission constraints at the sub-national level, which is already a challenge in some countries. Such high-level representation means that VRE curtailment and unserved energy demand are inherently underestimated and are only present in modelling when quite severe. To compensate for this, pumped hydro was not considered in the analysis, as a lack of sub-national transmission constraints would lead to overly optimistic results driven by high use of the large pumped hydro capacity existing today and additional expected capacity in the Transforming Energy Scenario.

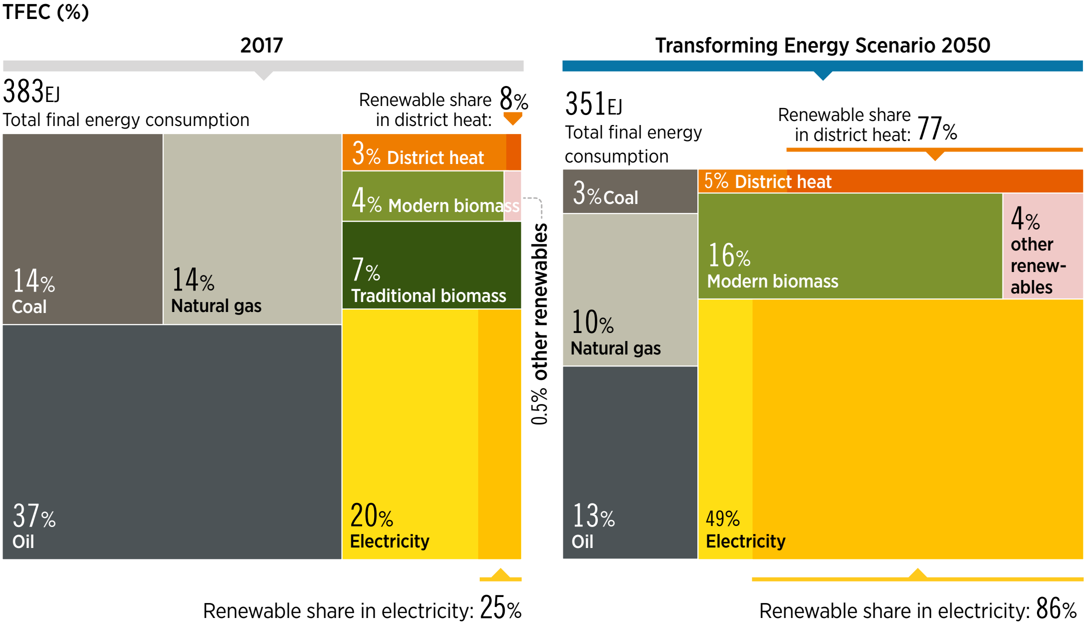
The main sources of flexibility to achieve a system with low curtailment and negligible unserved energy are: large-scale deployment of EVs with a combination of smart charging and vehicle-to-grid capacities, hydrogen production using electrolysis, battery storage and demand response. Interplay among different flexibility options such as these is fundamental; some are complementary (*e.g.*, batteries and hydrogen), but most will compete against each other, such as vehicle-to-grid, demand-side management and batteries, as found in this analysis. The analysis shows that the energy transformation requires not just technology deployment, but also the integration of different technologies.

The results of this analysis reveal that most technical solutions for an operable 2050 Paris-compliant power system are available today. For some of the solutions that remain on the horizon (*e.g.*, low inertia/synthetic inertia operations), a variety of technical measures are being trialled in front-runner countries. However, additional challenges may appear when moving beyond the Transforming Energy Scenario, from an 86% to a 100% renewable power system. A completely decarbonised power system will need new solutions, some of which are under discussion (*e.g.*, seasonal storage enabled by green gas from renewable power), to close this gap.

IRENA's model-based analysis, performed using the commercial power system software PLEXOS, shows how flexibility can make a Paris-compliant power system operable and how such operations are likely to look by mapping potential challenges that need to be addressed to make this happen, from market and regulatory design to control of distributed assets in close-to-real-time.

Due largely to increased renewable electrification and direct renewables use, the share of renewable energy in total final energy consumption (TFEC) would also rise considerably. The Planned Energy Scenario sees an increase in the share of renewables in TFEC from 17% in 2017 to 25% by 2050. The Transforming Energy Scenario results in a much higher share of 66%. Therefore, more than a six-fold acceleration in the percentage point (ppt) increase in the renewable energy share would be needed (from around 0.25 ppt/yr increase in the Planned Energy Scenario, to almost 1.5 ppt/yr) to raise the overall share from 17% to 18.5% in the first year and then incrementally to reach 66% in 2050 (Figure 1.8).

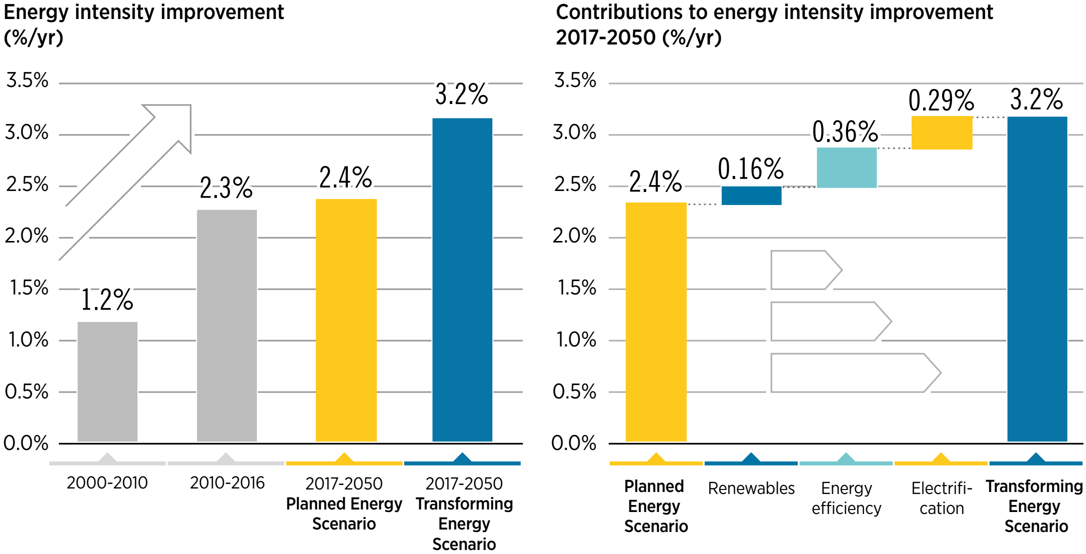
Figure 1.8 Renewable electricity: The world's largest energy carrier by 2050
Breakdown of total final energy consumption by energy carrier in 2017 and in the Transforming Energy Scenario 2050 (EJ)



Note: TES (IRENA), 2017 values based on IEA (2019b)

The energy intensity of the global economy would fall two-thirds by 2050 in the Transforming Energy Scenario. In recent years, energy intensity has been improving at around 2.3% per year; however, it is projected to have decreased to just above 1% in 2018. Nonetheless, the Planned Energy Scenario projects that this will accelerate to 2.4% per year. The Transforming Energy Scenario results in an energy intensity improvement of 3.2% per year (Figure 1.9). Energy intensity improvements are driven by electrification, renewable energy and energy efficiency.

Figure 1.9 Energy intensity improvement rate: 3.2% increase needed yearly
Energy intensity improvement and its contributions from Planned Energy Scenario to the Transforming Energy Scenario, 2017-2050



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

Based on IRENA analysis

Box 1.4 ELECTRIFICATION WITH RENEWABLES: DRIVING THE TRANSFORMATION OF ENERGY SERVICES

A far-reaching energy transition is required to address the urgent need to combat climate change and to develop sustainably. In this transition, clean electricity will become the principal fuel, combined with "smart" digital technologies that make it possible to take full advantage of the growing amounts of cheap renewable power.

Electrification with renewables unlocks the potential synergies between major increases in the use of electricity and renewable power generation by co-ordinating their deployment and use across demand sectors: power, transport, industry and buildings. Costs of renewable electricity, namely from wind and solar PV, have continued to decline rapidly and are set to fall further as installed costs drop and performance continues to improve, making these technologies competitive compared to all fossil fuel generation sources.

Thanks to its versatile nature as an energy carrier that can be used for almost all end-uses, electricity represents a low-cost option to decarbonise the energy sector. At the same time, the electricity generated by renewables can vary depending on prevailing weather conditions and having a high share of VRE in a power system poses increased operational challenges.

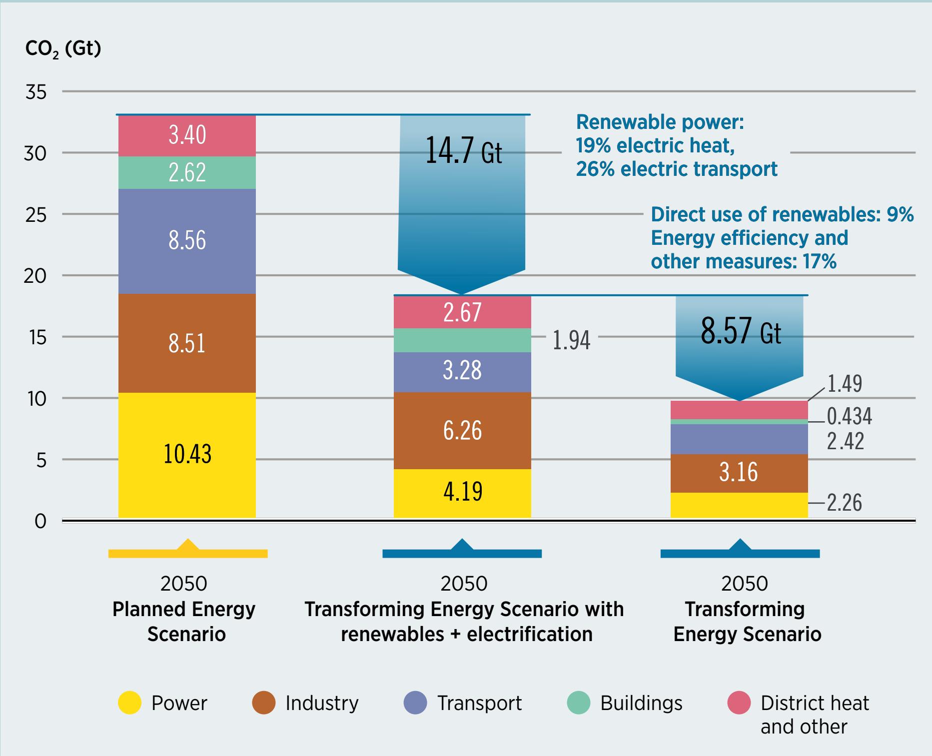
Electrification with renewable energy strategies meets these emerging operational challenges by looking beyond the generation side of the power system and tapping all available sources of flexibility. This includes the use of smart digital devices, information technologies, active demand management, energy storage, network interconnections and power-to-X carriers. As such, smart electrification with renewables creates a virtuous cycle, where electrification drives new uses and markets for renewables, which then accelerates the switch to electricity for end-uses, creating more flexibility and thus driving further renewables growth and technological innovation. Growth and innovation also reduce costs and create additional investment and business opportunities.

In addition, sector coupling would make a significant contribution to climate goals (BNEF, 2020). IRENA's work on the landscape of innovations shows how sector coupling opens new flexibility opportunities for integrating VRE into the grid (IRENA, 2019j).

The shift to renewable energy could reduce CO_2 emissions from the power sector by 64% compared to the Planned Energy Scenario, while deep electrification of the end-use sectors could reduce emissions from buildings, transport and industry by 25%, 54% and 16%, respectively. As a result, as seen in Figure 1.10, the overall impact of electrification with renewables would reduce total energy sector emissions by more than 60% compared to the Planned Energy Scenario. Adding direct use of renewable energy (such as solar thermal for heating or biofuel for transport) and efficiency measures would achieve emissions reductions of more than 90%, which is compatible with the well-below 2 °C climate goal established in the Paris Agreement.

Figure 1.10 Electrification with renewables: Ensuring 60% lower energy-related CO_2 emissions in 2050

Transforming Energy Scenario CO_2 reductions from electrification with renewables vs. other reduction measures in 2050



Based on IRENA analysis

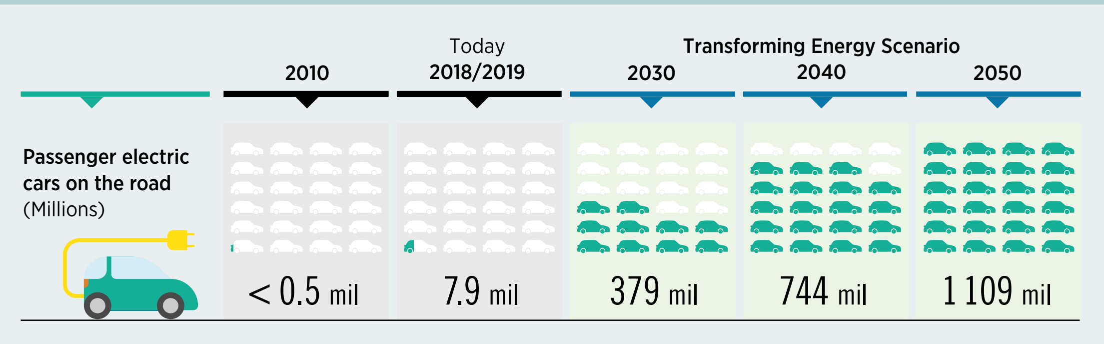
Box 1.5 SMART CHARGING FOR ELECTRIC VEHICLES

The advent of electric vehicles promises to be a game changer for the world's shift to sustainable energy and particularly to renewable power generation. Along with transforming the transport sector, EVs present a viable opportunity to introduce much higher shares of renewables into the overall power generation mix. Such developments offer a tantalising prospect – particularly for cities – to decarbonise transport while also cutting air and noise pollution, reducing fuel import dependence and adopting new approaches to urban mobility.

Steady cost reductions for renewable power generation make electricity an attractive low-cost energy source to fuel the transport sector. Scaling up EV deployment also represents an opportunity for power system development, with the potential to add much-needed flexibility in electricity systems and to support the integration of high shares of renewables.

Some regions, such as the European Union, are decisively promoting electromobility. Some EU countries have ambitious objectives to phase out internal combustion engine sales by 2030-2040. Further, in April 2019 the European Parliament and the Council adopted Regulation (EU) 2019/631, which sets CO_2 emissions performance standards for new passenger cars and light commercial vehicles in the region after 2020. From 2021, the EU fleet-wide average emissions target for new cars will be 95 grams of CO_2 per kilometre. EVs are now the only available option to comply with this limit, but the electricity fuelling the cars must

Figure 1.11 Low-cost electricity for transport
Total electric cars between 2010 and 2050 in the Transforming Energy Scenario (Millions)

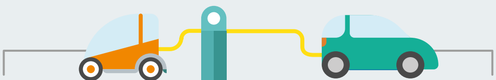


Note: 2019 data based on Spiegel (2020)

be renewable. Therefore, EV deployment must go hand in hand with more rapid penetration of renewables in the electricity mix.

Cars today, including EVs, typically spend around 95% of their lifetime parked. These idle periods, combined with battery storage capacity, could make EVs an attractive flexibility solution for the power system. Each EV could potentially become a micro grid-connected storage unit that provides a broad range of services to the system. On the other hand, the impact of uncontrolled charging on peak demand can be great. Simultaneous and uncontrolled charging of EVs during the mornings or evenings may exacerbate stress on the distribution grid and increase peak loads. While the growth in total electricity demand may be marginal, the increase in loads may require large investments to reinforce local grids. Smart-charging approaches, which adapt charging cycles via dynamic pricing and digital technologies, would therefore be crucial. They can reduce the distribution grid investments needed for the uptake of EVs between 40% to 90% based on country and grid conditions.

Figure 1.12 Smart charging: System-level and local flexibility via electric vehicles
Range of flexibility services provided by electric vehicles



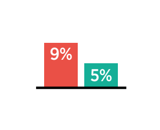
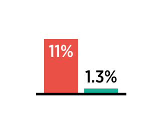
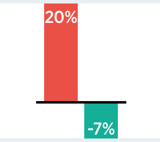
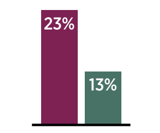
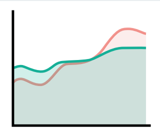
SYSTEM FLEXIBILITY		LOCAL FLEXIBLILITY	
Wholesale market	**Transmission System Operator**	**Distribution System Operator**	**Behind-the-meter**
• Peak-shaving • Portfolio balancing	• Frequency control (primary, secondary and tertiary reserve) • Other ancillary services (*e.g.*, voltage management emergency power during outages)	• Voltage control • Local congestion and capacity management	• Increasing the rate of renewable energy self-consumption • Arbitrage between locally produced electricity and electricity from the grid • Back-up power

Source: IRENA (2019j)

Box 1.5 SMART CHARGING FOR ELECTRIC VEHICLES (continued)

Figure 1.13 Technologies, business models and regulatory frameworks for EV smart charging

Impact of electric vehicle smart charging on the electricity grid

Study	Scenario	Uncontrolled charging	Smart charging	
IRENA	50% penetration in an isolated system with 27% solar share	↑ 9% increase in peak load, 0.5% solar curtailment	↑ 5% increase in peak load (V2G) Down to 0% curtailment	
RMI, 2016	23% penetration US (California, Hawaii, Minnesota, New York, Texas)	↑ 11% increase in peak load	↑ 1.3% increase in peak load (V1G)	
Taljegard, 2017	100% penetration Denmark, Germany, Norway and Sweden	↑ 20% increase in peak load	↓ 7% decrease in peak load (V2G)	
McKenzie, 2016	50% penetration in Island of Oahu, Hawaii, US 23% VRE share	10-23% VRE curtailment without EVs	8-13% VRE curtailment with smart charging EVs	
Chen and Wu, 2018	1 Million EVs in Guanzhou region, China	↑ 15% increase in peak load	↓ 43-50% reduction in valley/ peak difference	

● Peak load with uncontrolled charging
● Peak load with smart charging
● Curtailment in no EVs scenario
● Curtailment with smart charging EVs

Source: IRENA (2019j)

Smart charging could provide flexibility at both the system and local levels. At the system level, smart charging could facilitate balancing in the wholesale market. Depending on the type of smart charging, the EV charging patterns could be controlled to flatten peak demand, fill load valleys and support real-time balancing of the grid by adjusting their charging levels. Also, by injecting electricity back to the grid, EVs could provide ancillary services to transmission system operators. At the local level, smart charging could help distribution system operators manage congestion and could help customers manage their energy consumption and increase their rates of renewable power self-consumption.

Emerging innovations in smart charging for EVs span not just technologies but also business models and regulatory frameworks. These will be crucial to integrate renewable energy sources while avoiding network congestion. While incentives for smart charging infrastructure are in place, the actual deployment depends on market incentives. The potential is vast: by 2025, the car battery electricity storage capacity on the road may equal more than one-third of the hourly nameplate generation capacity in the EU.

IRENA's innovation outlook on smart charging for electric vehicles investigates the complementarity potential between VRE sources – solar PV and wind power – and EVs and considers how this potential could be tapped through smart charging up to mid-century (IRENA, 2019j).

Box 1.6 BIOENERGY

Bioenergy is the largest form of renewable energy in use today, globally accounting for 70% of the renewable energy supply and for 10% of the total primary energy supply. The largest share of bioenergy use is in the industry sector. About one-quarter of the bioenergy is used in the transport sector, mostly in the form of liquid biofuels from crops such as sugar cane and maize. The rest is used for cooking, heating and power, through combustion of feedstocks such as wood and straw.

Cooking with biomass is done largely outside of the modern energy sector in developing countries. Inefficient traditional cookstoves paired with solid fuels and kerosene emit indoor smoke that imperils the health of mainly women and children and causes nearly 4 million premature deaths every year. Much of the wood fuel used in the stoves is collected in an unsustainable manner from local forests, which is a major driving force of deforestation and forest degradation. Thus, detrimental cooking practices must be replaced with clean, efficient, modern energy-use systems that use improved cookstoves fuelled with sustainably produced bioenergy such as wood, biogas or ethanol (IRENA, 2017a).

Heating with biomass includes both high-temperature process heat for industry and low-temperature space heating for homes, apartments and office buildings. The agro-processing industry gets heat using crop residues from farms, while lumber, pulp and paper industries get heat using wood residues from forests. Buildings can be heated through town-scale district heating systems or building-scale furnaces, both of which use feedstocks such as wood chips and pellets very efficiently. There is a large potential to expand wood production through improved management of existing forests, as exemplified in Sweden where the volume of standing trees has doubled over the last century (IRENA, 2019k).

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

An important niche that will need to be efficiently explored is the use of biomass residues generated in bio-based industries such as pulp and paper, lumber and timber, and food processing and biofuels. These sectors usually offer large amounts of biomass resources that can be used for energy production. To a large extent, the modern part of those industries already taps into those resources, mostly for electricity and heat generation, in stand-alone applications or co-generation systems. Other less readily available biomass resources are often not used at all. In those situations, specific policies providing incentives for the use of this additional biomass are fundamental.

Transport fuels from biomass would be indispensable for decarbonising the global economy. Transport will become much more electrified, but not everywhere, not in all sectors and not all at once. It follows that there would be a large need for biofuels for several decades to come. While EVs will come to dominate light vehicle fleets and will be powered increasingly by renewable electricity, they can only enter markets with well-developed power grids and charging infrastructure. Moreover, fleets take two decades to turn over. Heavy long-distance freight trucks, marine ships and airplanes are unlikely to be fully electrified due to the higher energy density they require. Hence, all forms of biofuels have to be deployed more widely as the immediate climate solution (IRENA, 2020b). While technical and institutional challenges remain in scaling up the deployment of advanced biofuels, conventional biofuels (for example, sugarcane ethanol) have huge potential for increasing production capacity in Africa (IRENA, 2019l).

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

Bioenergy could bring synergies for enhancing food supply and restoring degraded land. There is excellent potential for farmers to raise wood in an agroforestry approach in which nitrogen-fixing wood crops naturally fertilise food crops planted alongside them (IRENA, 2019k). Short-rotation wood crop cultivation on degraded land can provide multiple socio-economic and environmental benefits, such as enhancing energy security without constraining food crops or other land-use options; greatly increasing the productivity of the land; providing extra financing incentive that could in turn increase the likelihood of success for land restoration commitments; lightening the burden of women and children collecting firewood over long distances; and generating employment and income, thereby reducing poverty (IRENA, 2017b).

Advanced biofuels need stable regulations and technology development. The vast demand for biofuels in the low-carbon transport sector pathway requires greater investment, estimated at more than USD 20 billion per year. Regulatory uncertainties are one of the most important barriers to ramping up the investments to the level needed. Other barriers are the cost and availability of financing, and the high costs of biofuels production compared to other fuels (IRENA, 2019m).

Even though almost half of final energy use would be sourced from electricity, fuels and other direct uses of energy would still make up half of energy demand. In the transport and industry sectors, the share of electricity would increase to around 40% by 2050, with most of the energy still coming from fuels.

Modern bioenergy can play a vital role in the energy transition if scaled up significantly. Although greater amounts of modern bioenergy, such as liquid biofuels and biomass pellets, have been used in recent years, its growth pace is insufficient to support the requirements of the energy transition. A much stronger and concerted effort is needed, particularly in sectors for which bioenergy could provide key solutions (shipping, aviation and various industrial applications). Primary modern bioenergy demand would grow from around 30 exajoules (EJ) in 2016 to 125 EJ by 2050 in the Transforming Energy Scenario. Liquid biofuels consumption would reach 652 billion litres, up from 129 billion litres in 2016.

Bioenergy will have to be sourced from sustainable and affordable feedstocks, such as agricultural and forestry residues or municipal solid waste. Inefficient traditional cookstoves emit indoor smoke that imperils the health of mainly women and children. Much of the wood fuel they use is collected on an unsustainable basis from local forests. They must be replaced with clean and efficient modern cookstoves, which must be fuelled with sustainably produced wood or ethanol. There is excellent potential for farmers to raise wood in an agroforestry approach in which nitrogen-fixing wood crops naturally fertilise food crops planted alongside them.

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

Hydrogen has emerged as an important part of the clean energy mix needed for a sustainable future. Important synergies exist between hydrogen and renewable energy, as hydrogen can boost renewable electricity market growth and broaden the reach of renewable solutions. Electrolysers can add demand-side flexibility and offer seasonal storage of solar and wind power. Falling costs for hydrogen produced with renewable energy, combined with the urgency of cutting greenhouse gas emissions, have given clean hydrogen unprecedented political and business momentum.

The energy transformation will require widespread and profound changes in all sectors of the energy system. Integrated energy planning will be required that combines a holistic perspective on energy system and long-term planning to successfully achieve the energy transformation and capture its many benefits. The government institutions have important roles to play in ensuring that energy planning involves all key stakeholders, including energy producers, energy consumers, financial institutions and private investors. For instance, in the transport sector, energy and digital and information technologies infrastructures should be planned in an integrated manner across the sectors, and the necessary costs and taxation systems should be well aligned with the overall energy transition targets and benefits.

Figure 1.14 shows some of the key energy system indicators that can be used to track the progress of the energy transformation.

Figure 1.14 System-wide transformation: Changes in all sectors of energy use

A roadmap to 2050: Tracking progress of key energy system indicators to achieve the global energy transformation

	2010	Today 2017*/2018/ 2019e**	Transforming Energy Scenario 2030	2040	2050	On/Off track	Implications
Electrification with renewables							
Share of electricity in final energy consumption (TFEC)	18%	20% *	29%	38%	49%	Off track	Focus on electric mobility and electrifying heat in buildings and industry, and on synthetic fuels and feedstocks – see further recommendations below.
Renewable energy share in power generation	20%	26%	57%	75%	86%	Progress	Emphasise solar and wind deployment, but also maximise solid biomass and biogas in the niche applications where they make sense.
Annual solar PV additions	17 GW/yr	93** GW/yr	300 GW/yr	355 GW/yr	360 GW/yr	Progress	Accelerate solar deployment by reinforcing existing policy and market support.
Annual wind additions	31 GW/yr	60** GW/yr	200 GW/yr	210 GW/yr	240 GW/yr	Off track	Plan for wind industry and required logistics to enable accelerated deployment. Consider the large potential of offshore deployment.
Passenger electric cars on the road	<0.5 mln	7.9 mln **	379 mln	744 mln	1109 mln	Progress	Enact measures to support getting electric cars purchasing price down and invest heavily in charging infrastructure.
Heat pumps		38 mln	155 mln	259 mln	334 mln	Off track	Promote public awareness about the advantages of heat pumps and create special lines of finance to project developers that can disseminate the technology.
Hydrogen production with renewable electricity		0.16 EJ	3 EJ	8 EJ	19 EJ	Emerging	Find the niches where this makes sense today and support commercial-scale pilot projects.
Renewable energy in end uses							
Total renewable energy share increase in TFEC relative to today		0.2 ppt/yr	0.8 ppt/yr	1.2 ppt/yr	1.7 ppt/yr	Off track	Besides electrification, keep strong focus on solar thermal heating in buildings and liquid biofuels in transport.
Solar thermal collectors	290 mln m²	686 mln m²	2000 mln m²	3800 mln m²	5800 mln m²	Progress	Promote public awareness about the advantages of solar thermal and create special lines of finance to project developers that can disseminate the technology.
Transport liquid biofuels	100 bln litres/yr	136* bln litres/yr	378 bln litres/yr	510 bln litres/yr	652 bln litres/yr	Off track	Start with long-term, credible blending mandates and increase the use of advanced biofuels for domestic and international shipping and aviation.

Note: The findings in this report consider targets and developments as of April 2019. The wind and solar PV capacities in Transforming Energy Scenario in 2030 in this report are slightly higher than the estimates presented in IRENA's reports (IRENA, 2019d; 2019e) which consider developments as of the third quarter of 2019. Today LCOE values are G20 weighted averages.

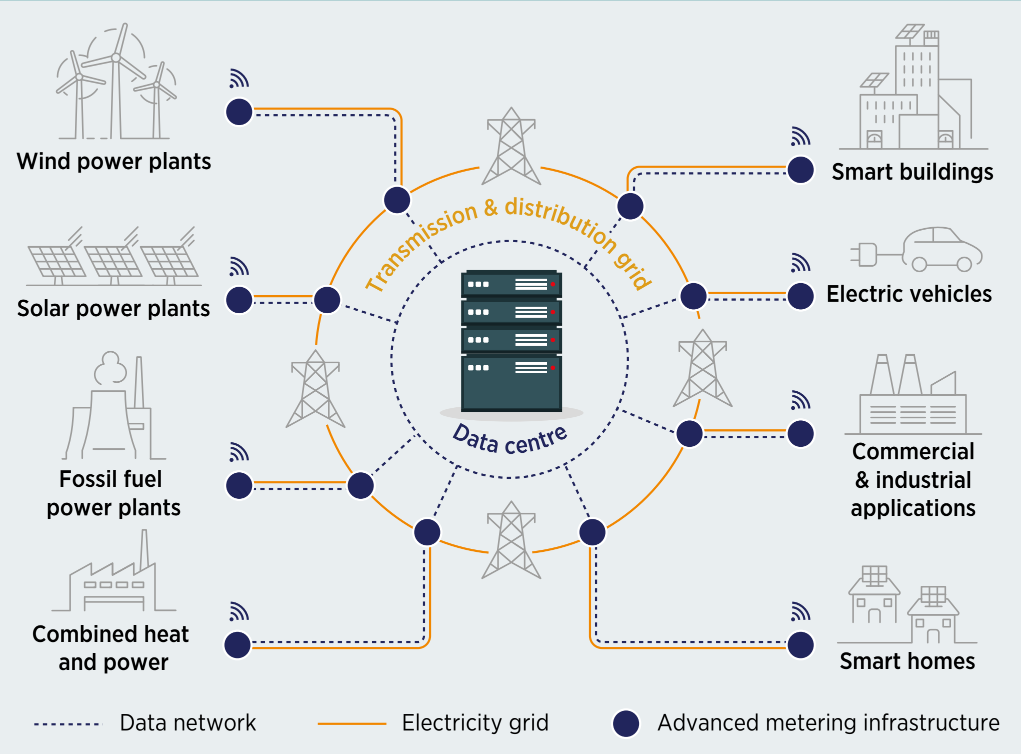
Note: IRENA analysis and today values based on IRENA (2019d, forthcoming a), GWEC (2020), Spiegel (2020), Global Carbon Atlas (2019), IEA (2019a, 2019b).

	2010	Today 2017*/2018/ 2019e**	Transforming Energy Scenario 2030	2040	2050	On/Off track	Implications
Energy efficiency							
Energy intensity improvement rate	2000-2010 1.2% per year	2010-2017 2.3% per year	2017-2030 3.3% per year	2017-2040 3.3% per year	2017-2050 3.2% per year	Off track	Promote efficiency standards and efficient appliances and create conditions for project developers that speed deployment of energy efficiency technologies.
Total final energy consumption per capita	51 GJ per cap	55 GJ per cap	43 GJ per cap	41 GJ per cap	38 GJ per cap	Off track	
Electricity generation and consumption aspects							
Onshore wind LCOE	80 USD/MWh	55 USD/MWh	50 USD/MWh	45 USD/MWh	40 USD/MWh	On track	Promote competitive bidding for solar and wind capacity additions and reform market regulation to accommodate these sources
Solar PV LCOE	347 USD/MWh	96 USD/MWh	58 USD/MWh	48 USD/MWh	38 USD/MWh	Progress	
Smart meters in the residential sector		25% of households	50% of households	77% of households	82% of households	Progress	Accelerate smart meter installations in existing buildings and mandate their installation in new buildings.
Total fossil fuel demand							
Oil demand	87 mln barrels/day	97 mln barrels/day	60 mln barrels/day	41 mln barrels/day	22 mln barrels/day	Off track	Increase liquid biofuels and electrification in the transport sector. Support pilot projects for bio-refineries and synthetic feedstock use for petrochemicals in industry.
Natural gas demand	3307 bcm/yr	3952 bcm/yr	4000 bcm/yr	3400 bcm/yr	2250 bcm/yr	Off track	Push renewable hydrogen, solid biomass and electrification in the buildings and industry sectors on top of strong energy efficiency measures.
Coal demand	4963 Mtce/yr	5458 Mtce/yr	3190 Mtce/yr	2000 Mtce/yr	713 Mtce/yr	Off track	Stop building new coal power plants and accelerate the retirement of existent coal power facilitieis. Need for new carbon-free iron making processes.
Total fossil fuel reduction relative to today			-20%	-41%	-64%	Off track	End subsidies for fossil fuels. Support training programmes to retrain displaced workers from fossil fuel industries.
Energy-related CO_2 emissions							
Total CO_2 reduction relative to today			-27%	-48%	-71%	Off track	Correct market distortion and price the external costs of CO_2. Avoid fossil fuel infrastructure stranding by avoiding unnecessary investment in new production and distribution.
Emissions per capita	4.3t CO_2 per cap	4.4t CO_2 per cap	2.9t CO_2 per cap	2.0t CO_2 per cap	1.1t CO_2 per cap	Off track	

Box 1.7 STEPPING FORWARD TO A DIGITALISED AND INTERCONNECTED WORLD

Digitalisation is a key amplifier of the power sector transformation, enabling the management of large amounts of data and optimising increasingly complex power systems. Our increasingly digitalised world is becoming ever more interconnected. The growing importance of digitalisation in the power sector is partially a consequence of increasing decentralisation (*e.g.*, increased deployment of power generators at the distribution level) and electrification (*e.g.*, the emergence of EVs, heat pumps and electric boilers). Recent analysis from IRENA shows how all these new small and distributed assets on the supply and demand sides are adding complexity to the system and making monitoring, management and control crucial for the success of the energy transition.

Figure 1.15 Internet of Things (IoT) as a driver for power system transformation
Internet of Things in context: Smart grids connecting smart devices from both the demand and supply sides



Source: IRENA (2019n)

The Internet of Things (IoT) is one of the digital technologies that can support the energy transition. Simply put, the IoT transforms physical objects into "smart" devices to collect, communicate, monitor and interpret information from their surroundings in real time.

IRENA has studied the role of the IoT in power sectors with rapidly increasing shares of renewables. IoT applications enable "smart grids" by enhancing the visibility and responsiveness of grid-connected devices. For example, IoT technology has the potential to increase the visibility, flexibility and responsiveness of grid-connected smart assets for the system operator. Such innovations range from sensors that enable data gathering to automated control (*e.g.*, smart thermostats maximising energy efficiency by adjusting the temperature of consumers' homes depending on whether they are at home).

By connecting energy suppliers, consumers and grid infrastructure, IoT technology facilitates the bi-directional flow of data, the operation of increasingly complex power systems (which benefit the most from IoT integration) and the establishment of new business models by enabling clients to further monetise the value created by their assets through demand-side management.

IoT technologies, and in particular the data that the devices generate and the automated control they provide, are underpinning a historic transformation that will lead to cleaner, more distributed and increasingly "smart" grids. Access to more, higher-quality data across the whole value chain enables better decision-support tools (such as artificial intelligence) and enables remote control and automated execution of decisions (*e.g.*, control of millions of devices with immediate actions, such as algorithm trading or self-driving cars).

The rise of the IoT enables the use of artificial intelligence, powered by big data, as it provides the granular information needed to feed machine learning algorithms. **Blockchain is another digital technology that has a role to play in complex power systems**, decreasing transaction costs by managing data more openly and securely while automating transactions via smart contracts.

By 2025, 75 billion devices worldwide are expected to be Internet connected, providing a wealth of information to consumers, manufacturers and utility providers. The benefits of the IoT are manifold, but despite these benefits, IoT technology still faces serious challenges that need to be overcome before widespread implementation is possible. The biggest challenges are the reliability of the technology, data privacy and cybersecurity. These challenges could be overcome through effective collaboration among power and information technology companies, policy makers and regulators, and end-users. The explosion of data generated, due in part to the proliferation of IoT devices, will power new technologies and unlock new industries in the coming years and decades, leading the way to a renewable-powered future (IRENA, 2019o).

Box 1.8 SCENARIOS COMPARISON

Beyond IRENA's Transforming Energy Scenario, several other scenarios have recently been published to explore transition pathways for the energy system in the coming decades. These include, for comparison, one recent "forecast" scenario, DNV-GL's Energy Transition Outlook 2019 (DNV GL, 2019); one business-as-usual (BAU) scenario, McKinsey's New Global Energy Perspectives 2019 (McKinsey, 2019); and seven decarbonisation scenarios that claim compatibility with Paris Agreement targets: the IEA's 2019 "SDS" scenario (IEA, 2019a), Shell's 2018 "Sky" scenario (Shell, 2018), Greenpeace's 2015 "Advanced" scenario (Greenpeace, 2015), Equinor's 2019 "Renewal" scenario (Equinor, 2019), the scenarios in the "Achieving the Paris Climate Agreement Goals" report from the Institute for Sustainable Futures at the University of Technology Sydney (UTS-ISF, 2019), and the "Below 1.5°C" and "1.5°C High" scenarios from the Intergovernmental Panel on Climate Change (IPCC, 2018).

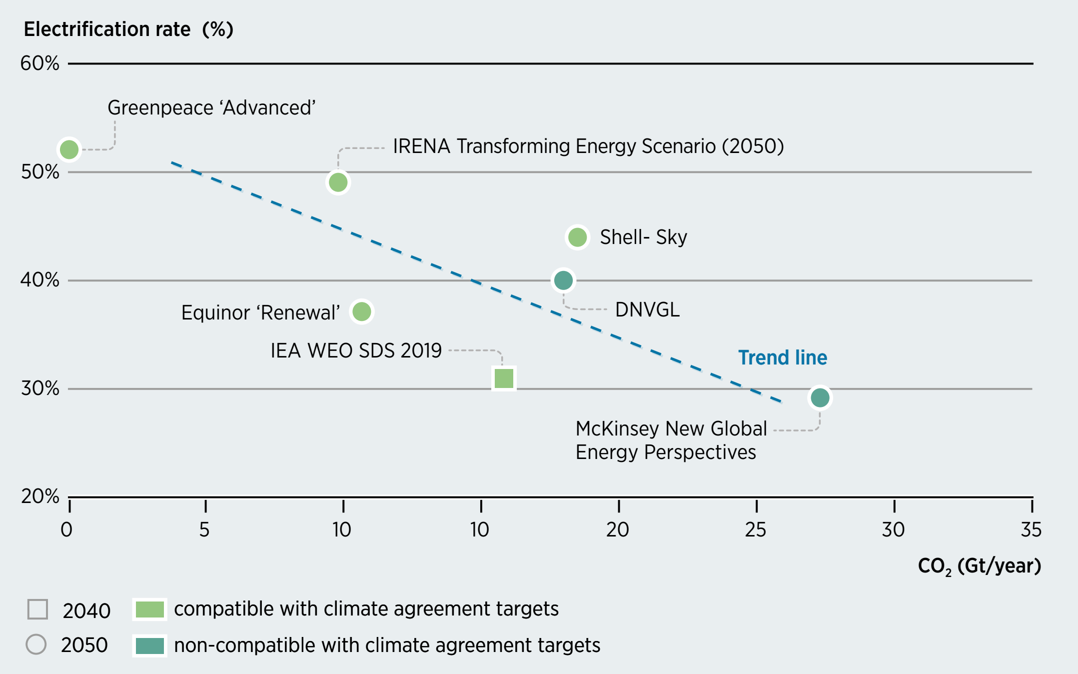
All of the scenarios examined, even when consistent with the Paris targets according to the scenario authors, show different visions of the future. This is not surprising, as it reflects the complexity and uncertainties in the energy transition and the different approaches and assumptions regarding the development of renewable energy, as well as the different combinations of electrification and emissions reductions strategies and overall carbon budgets.

Figure 1.16 shows the wide range of results regarding the degree of electrification and the depth of long-term decarbonisation realised by the scenarios considered.

The business-as-usual scenario (McKinsey's New Global Energy Perspectives 2019) estimates that the share of electricity in total final energy consumption will grow from current levels to around 29% by 2050. Under these same BAU scenario, global energy-related CO_2 emissions in 2050 would be around 27 Gt/year, far from compatible with the objectives of the Paris Agreement.

The recent forecast by DNV GL predicts a much faster transformation of the global energy sector, reaching an electrification share of 45% by 2050 together with global energy-related CO_2 emissions of 18 Gt/year in 2050, which, according to the authors, are incompatible with a 2°C pathway, despite the strong degree of electrification. Within the scenarios claiming compatibility with the Paris Agreement, the electrification share in 2050 varies substantially as well, from 31% in the IEA 2019 "SDS" scenario to 52% in the Greenpeace "Advanced" scenario. With a share of 49% of electrification in 2050, **IRENA's Transforming Energy Scenario is on the upper hand of the various forecasts, showing the importance of electrification in the energy transition.**

Figure 1.16 Different visions of the future: Scenarios presented in other major energy studies
Global energy-related CO_2 emissions in 2050 vs. electrification rate in various energy scenarios

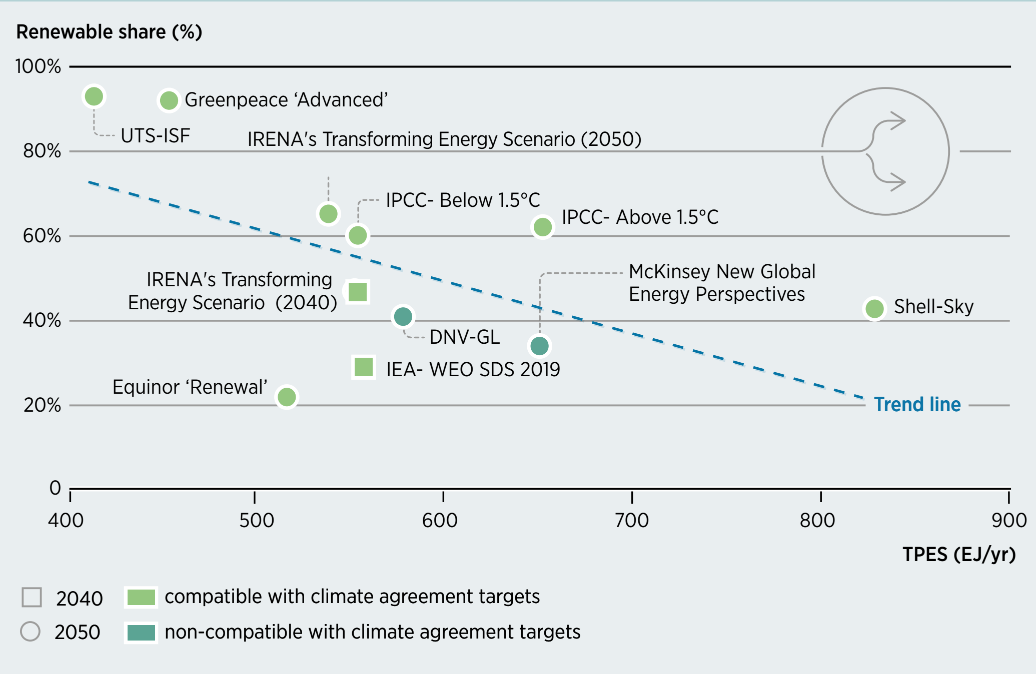


Source: DNV GL, McKinsey, Equinor, 2019; IEA, 2019a; Shell, 2018; Greenpeace, 2015

Box 1.8 SCENARIOS COMPARISON (continued)

Figure 1.17 shows the relationship between energy demand, energy efficiency and share of renewable energy in the scenarios considered. There are two main considerations. First, the scenarios with high renewable energy shares are also the ones with the lowest total primary energy supply. Second, there is a significant difference between achieving the 2 °C versus the 1.5 °C targets. While carbon emissions in the energy sector must be drastically reduced to achieve either climate target, achieving the 1.5 °C target would also require significant structural and lifestyle changes.

Figure 1.17 Emerging consensus on the role of renewable power
Shares of renewables in total primary energy in 2040 and 2050 in various climate scenarios



[1]IEA SDS 2018 data for 2050 are unavailable, 2040 data are shown.

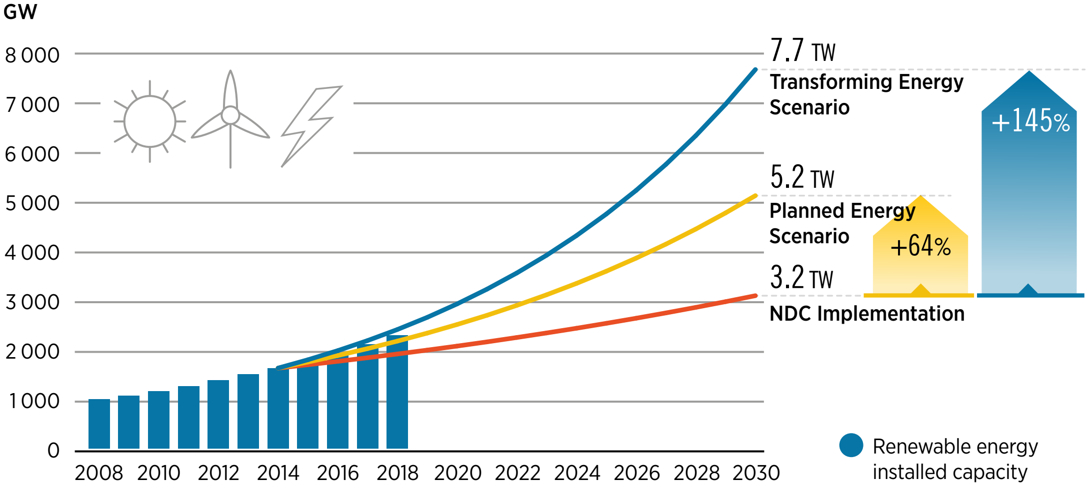
Source: DNV GL, McKinsey, Equinor, UTS-ISF, 2019; IEA, 2019a; Shell, 2018; Greenpeace, 2015

1.4 Outlook for 2030 and NDC formulation

National Determined Contributions (NDCs) are the backbone of the Paris Agreement, signed by the 197 member states of the United Nations Framework Convention on Climate Change (UNFCCC) in 2015. NDCs include mitigation actions, and in most cases adaptation actions as well, that a country can put in place to stay in line with the agreement. The year 2020 represents a significant milestone in global efforts to cut energy-related CO_2 emissions. As countries review and update their NDCs, they could simultaneously raise their ambitions to scale up renewable energy. The new NDC round offers an important chance to strengthen targets for renewables in the power sector and beyond.

Present NDC pledges are far from sufficient to meet climate goals. For example, within the power sector, current NDC power targets overlook 59% of the potential for renewable electricity deployment in line with the Paris Agreement by 2030. For a climate-compatible transformation, more extensive deployment of renewable generation capacity, amounting to 7.7 terawatts (TW) (or 3.3 times current global capacity), could be achieved cost effectively and would bring considerable socio-economic benefits (Figure 1.18).

Figure 1.18 Nationally Determined Contributions: Currently insufficient to meet Paris Agreement climate goals
Renewable energy installed capacity in different scenarios



Source: IRENA (2019b)

NDC power targets even fall short of countries' existing strategies and plans. Only 85 countries have included unconditional renewable power pledges in their current NDCs – compared to 135 with non-NDC domestic renewable power targets (either national or sub-national). Aligning the next round of NDCs closely to those real-world targets could increase global renewable power capacity to 5.2 TW (or 2.2 times current global capacity) by 2030.

NDCs do not reflect the actual growth of renewable power, with global capacity growing by an average of 8.6% per year since 2015. Implementing current NDCs would translate into annual capacity growth of only 4% for 2015-2030, even though annual renewable power growth already averaged 5.9% during 2010-2014. With current deployment trends, the 3.2 TW foreseen in current NDC power targets for 2030 would already be realised by 2022.

Under the Transforming Energy Scenario, the share of renewable energy in total final energy consumption would rise considerably from around 17% in 2017 to 28% by 2030. This is a much higher increase in renewable share when compared to the Planned Energy Scenario, where the share of renewables in TFEC would increase to only 19% by 2030 (Figure 1.19).

At a sectoral level, the buildings sector could have the highest share of renewable energy in TFEC, and overall renewables could ramp up to a 40% share by 2030, from 35% (when including traditional use of biofuels) or 13% (excluding traditional use of biofuels). (Figure 1.19) Energy efficiency is key and consists mainly of measures such as retrofitting, refurbishing and renovating buildings, and implementing stricter standards for domestic appliances and for emissions from new buildings.

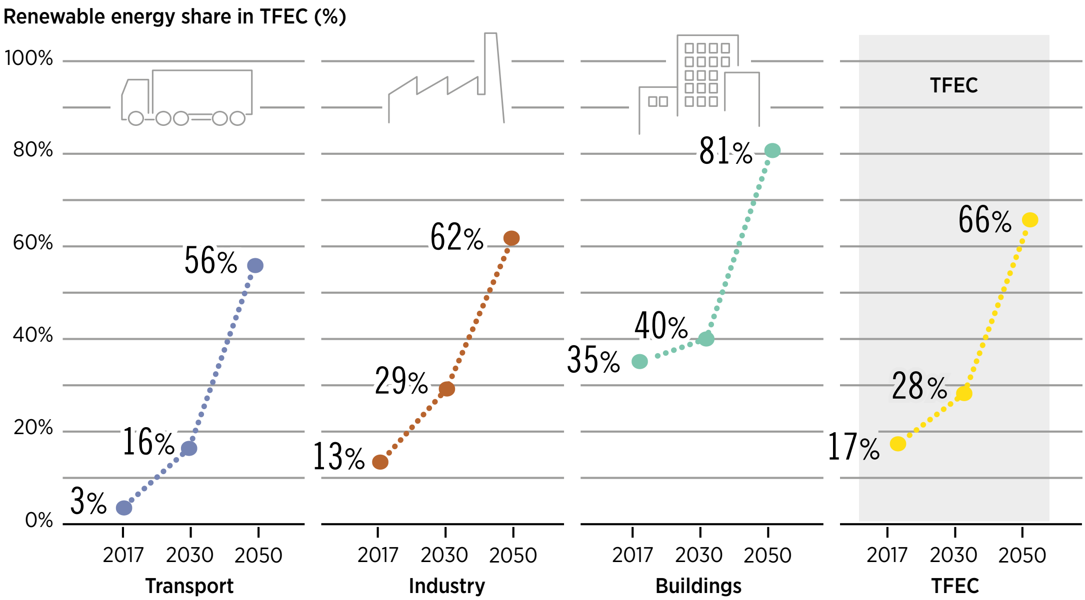
The second highest share would be in the industry sector, where renewables would reach a 29% share by 2030 from 13% in 2017. There is a large potential to improve efficiency in the industrial sector, and the global industrial energy consumption could be reduced by about a quarter thanks to improvements in industrial processes. Measures to improve efficiency or decrease consumption include setting or mandating minimum standards on energy efficiency and/or on the carbon intensity of fuels, adopting demand-side management solutions, developing material recycling and strengthening waste management.

The transport sector would have the lowest share, but the highest growth, with a 16% share of renewables in TFEC by 2030, compared to only 3% in 2017. Energy efficiency is critical for the transport sector. On the one hand, fuel efficiency can be achieved through the adoption of technologies, such as EVs, plug-in hybrid EVs and gasoline hybrid-electric vehicles, as they all have the potential to reduce petroleum use and greenhouse gas emissions. On the other hand, modal shifting also has a high energy efficiency potential. These shifts include innovative mobility services such as car sharing, increasing connectivity and autonomous driving.

Scaling up electricity from renewables is crucial for the decarbonisation of the world's energy system. Increasingly, electrification with renewables is seen as a major solution, and the contribution of renewable electricity will be the single largest driver for change in the global energy transformation. The Transforming Energy Scenario sets a pathway to achieve a 57% share for renewables in the power generation mix by 2030, up from 25% in 2017.

The role of electricity as an energy carrier will also increase, growing from a 20% share of final energy consumption to an almost 30% share in the Transforming Energy Scenario in 2030, with gross electricity consumption increasing 10 times from 25 600 terawatt-hours (TWh) in 2017 to 35 900 TWh in 2030. By 2030 in the Transforming Energy Scenario, one-third of the world's electricity would come from solar and wind power.

Figure 1.19 Renewable energy share needs to grow in all sectors
Share of renewable energy in total final energy consumption by end use in the Transforming Energy Scenario

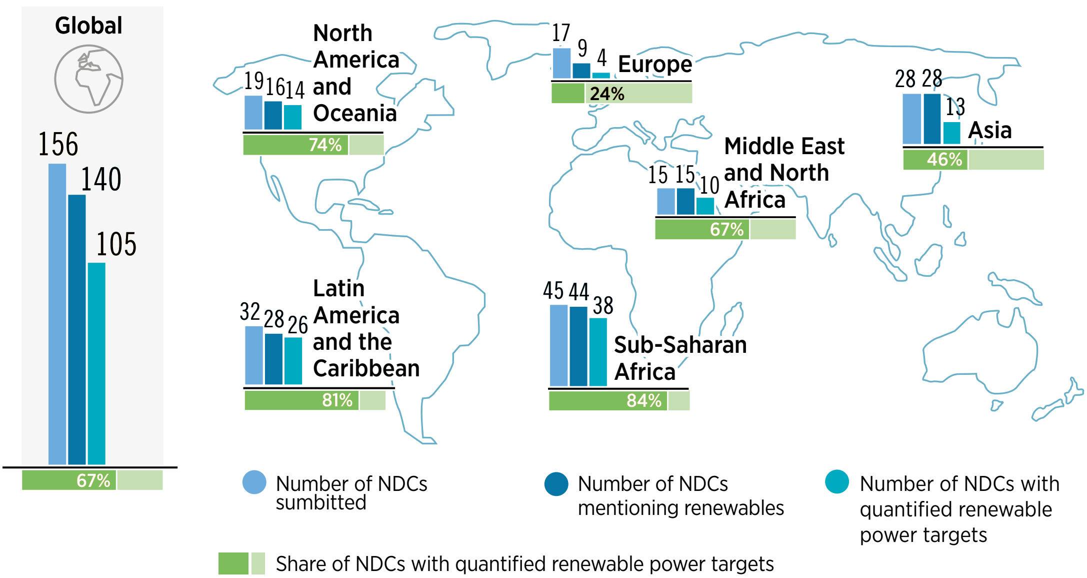


Note: TES (IRENA) 2017 values based on IEA (2019b)

Many countries recognise the need to scale up renewable power. To date, 135 countries have renewable electricity targets in their national and sub-national energy plans, and 140 NDCs mention renewables in the power sector. But only 105 NDCs include quantified targets for renewable electricity (Figure 1.20). To drive the changes needed for a climate-safe future, NDCs must become more ambitious in 2020, reaching for the levels necessary to meet climate goals and extending to end-uses, such as direct heat and transport.

Renewables provide a readily available climate mitigation and adaptation tool that supports multiple Sustainable Development Goals. With these aims at the forefront, NDCs in 2020 offer an immediate opportunity to strengthen renewable energy targets in the power sector and beyond.

Figure 1.20 NDCs with targets for renewables: Numbers by region
Number of NDCs with renewables targets



Source: (IRENA, 2019b)

Disclaimer: The designations employed and the presentation of material herein do not imply the expression of any opinion on the part of IRENA concerning the legal status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

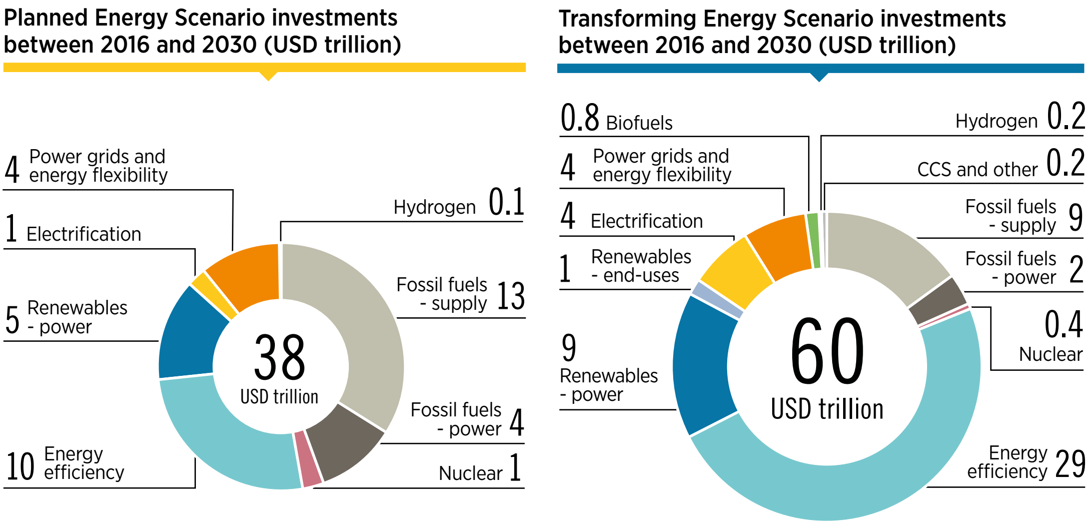
1.5 Investment must be redirected

Government plans in place today call for investing at least USD 95 trillion in energy systems over the coming three decades. But those plans and related investments are not always channelled towards climate-proof systems. The investments must be redirected. To ensure a climate-safe future, they need to flow into an energy system that prioritises renewables, efficiency and associated energy infrastructure.

IRENA's Transforming Energy Scenario shows that cumulative investments of nearly USD 10 trillion should be redirected from fossil fuels and related infrastructure to low-carbon technologies by 2030. Cumulative investments in the energy system over the period to 2030, including infrastructure and efficiency, would reach USD 60 trillion (Figure 1.21).

Nearly USD 9.6 trillion of cumulative investments would be needed to scale up renewable power generation capacity through 2030. In annual terms, this would imply doubling investments in renewable power generation capacity to USD 676 billion per year until 2030 compared to USD 289 billion invested in 2018 (FS-UNEP and BNEF, 2019).

Figure 1.21 Energy investments 2016-2030
Cumulative energy sector investments over the period to 2030



Based on IRENA analysis

Looking ahead to longer time horizons up to 2050, with a different energy investment mix and USD 15 trillion of additional investment, the global energy system could become much more climate friendly, with cost-effective renewable energy technologies underpinned by more efficient use of energy. USD 3.2 trillion – representing around 2% of GDP worldwide – would have to be invested each year to achieve the low-carbon energy transformation. This is around USD 0.5 trillion more than under current plans. While cumulative global energy investments by 2050 would then be 16% higher, their overall composition would shift decisively away from fossil fuels.

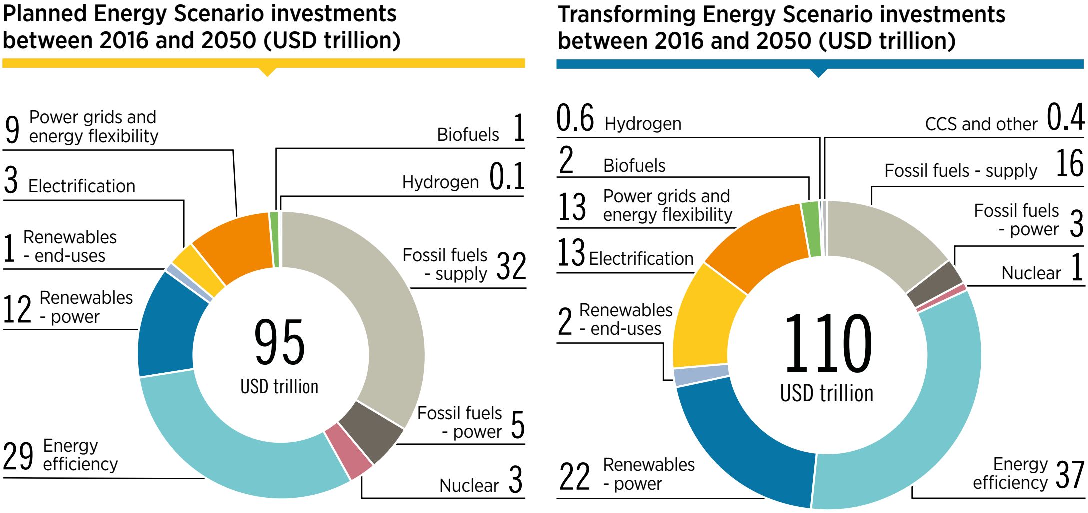
Renewables and associated infrastructure account for nearly half of the difference in total investment, with energy efficiency and electrified transport and heat applications absorbing the rest. Investment to build up renewable power generation capacity needs to be twice as high as currently foreseen, reaching USD 22.5 trillion by 2050 (Figure 1.22).

Energy efficiency requires investments of USD 1.1 trillion per year, more than four times the present level. With solar and wind power on the rise, grid operators need new equipment to make the whole power system operate flexibly. Some of the solutions are market based, while others require investment in modern technology solutions. Quick-ramping thermal generation back-ups, pumped hydro, reinforced transmission and distribution grids, digital control equipment, vastly expanded storage capacity, and demand-side management through heat pumps, electric boilers and behind-the-meter batteries are just some of the areas for power system investment.

Climate change impacts will result in high economic costs. More (and more severe) fires, floods, droughts and extreme weather will take larger economic tolls, which must be borne in the end by individuals (taxpayers) and governments. In addition, the health costs from pollution are of increasing concern for many cities, particularly in the developing world. The energy transition pathway presented in IRENA's Transforming Energy Scenario will avoid between USD 65 billion and USD 157 billion in additional annual external costs related to climate and air pollution in 2050, costs that would otherwise have to be internalised in the financial system by banks and governments.

In addition, delaying action on accelerating the energy transition will almost double the amount of stranded assets. Those additional stranded assets will have a value of USD 7 700 billion over the period to 2050 that will have to be written off on the balance sheet of companies, public utilities or governments. As one of the policy measures to reduce stranded assets, countries are already paying for accelerated coal plant closures. Germany's phase-out of coal plants is costing USD 44 billion (Wacket, 2019), for example, while the Netherlands and several US states are absorbing the costs using securitisation bonds.

Figure 1.22 Energy investments 2016-2050
Cumulative energy sector investments over the period to 2050



Based on IRENA analysis

Several innovations are happening in the area of financing clean energy projects:

- Central banks, financial institutions and insurance companies are starting to take note and incorporate climate risk into their financial planning assessments. The Bank for International Settlements recently launched an open-ended fixed income fund (Hinge, 2019) – a "green bond fund" for central banks.
- The International Monetary Fund recently announced that it would integrate environmental risks as part of its economic analysis of counties, and that some countries are at high risk of "carbon shocks" to their economies (Healy, Marchand, 2019).
- The CEO of Blackrock announced a change in investment strategy, saying that climate change has put the world "on the edge of a fundamental reshaping of finance" (Fink, 2020).
- Additionally, some groups are starting to talk about trade measures that could be levied on countries that do not adequately address their carbon emissions – for instance, carbon tariffs could be placed on imports from countries that are deemed to be acting too slowly to address emissions.

To help navigate these new and innovative investment waters and to accelerate a shift of finance into climate-friendly technologies, IRENA is working with partners on the **Climate Investment Platform (CIP)**[1] towards unlocking financial resources for the clean energy transition, particularly in developing countries. By addressing the key risks and barriers that hinder the scale-up of clean energy investment, CIP will accelerate the low-carbon energy transition and promote sustainable growth.

[1] For more details, see www.climateinvestmentplatform.com.

02

GLOBAL SOCIO-ECONOMIC IMPACT

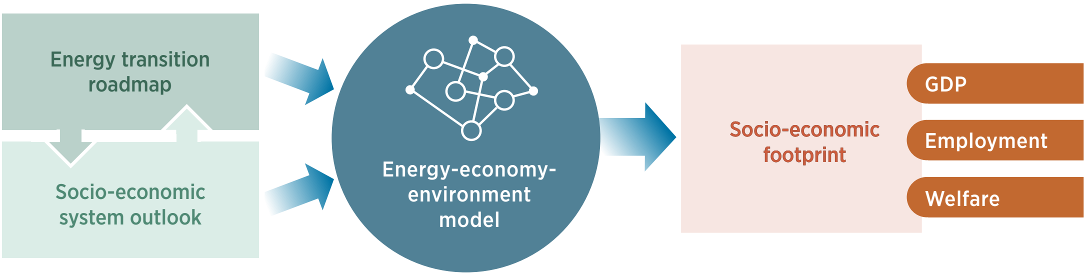
Renewable energy technologies are at the heart of the needed energy transition. The roadmap for the transition points to a more sustainable energy system and lays the foundation for achieving socio-economic development. The energy transition discourse has thus far been largely technology-oriented and disconnected from the socio-economic aspects upon which it is built and its long-term sustainability depends. A true and complete transition includes both the energy and the socio-economic system transition, and their interlinkages. Therefore, a wider picture is needed, viewing energy and the economy as part of a holistic system.

Socio-economic footprint analyses (IRENA, 2016c, 2019a, 2020a) have captured an increasingly comprehensive picture of the impact of the energy transition. For these analyses, IRENA has undertaken a macro-econometric approach (via E3ME model) that links the energy system and the world's economies within a single and consistent quantitative framework, and analyses variables such as GDP, employment and welfare (Figure 2.1). Its results can inform energy system planning, economic policy making, and other policies undertaken to ensure a just and inclusive energy transition at the global, regional and national level. Forthcoming IRENA analysis looks at structural and distributional impacts of transition pathways, which may become increasingly relevant in the current global situation.

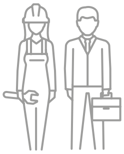
The socio-economic outcomes are explained through drivers fuelled by the energy transition: changes in investment, changes in trade flows and patterns, and indirect and induced effects, including those triggered by fiscal policy.

Section 2.1 identifies the key drivers of the energy transition's impacts on jobs and skills. Section 2.2 focuses on GDP. Section 2.3 presents the welfare indicator and associated impacts.

Figure 2.1 Close interplay between the energy sector and the economy
Sketching the socio-economic footprint of the transition



2.1 Jobs and skills

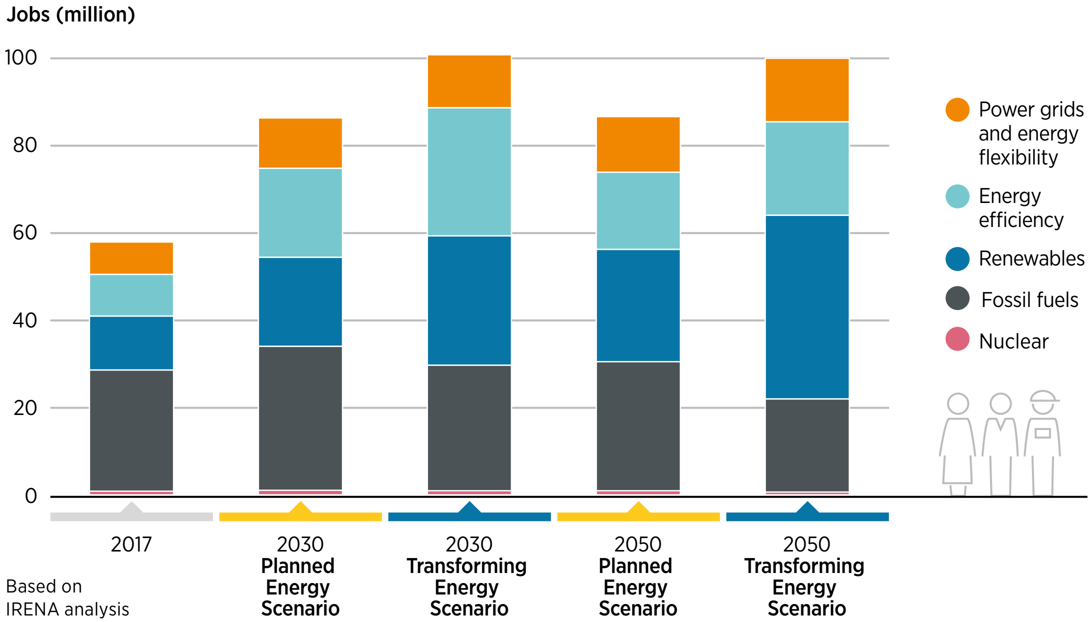


This section offers an overview of insights, first for the energy sector as a whole, then for its constituent parts (*i.e.*, transition-related technologies and conventional technologies). This includes an analysis of drivers of gains and losses, illustrated by four hypothetical cases. Finally, there is an analysis of impacts in the economy as a whole. All of these observations contrast the differences in outcomes under the Planned Energy Scenario and the Transforming Energy Scenario.

JOBS IN THE OVERALL ENERGY SECTOR

Under the Transforming Energy Scenario, jobs in the overall energy sector – comprising transition-related technologies (renewable energy, energy efficiency, and power grids and energy flexibility[1]), fossil fuels and nuclear power – could reach 100 million by 2050. Figure 2.2 presents estimates of overall energy sector jobs by 2030 and 2050 under the two scenarios, contrasting developments for segments of the energy sector.

Figure 2.2 Energy sector jobs growth: Reaching 100 million in 2050
Global energy sector jobs under the Planned Energy and Transforming Energy scenarios, in 2017, 2030 and 2050



Based on IRENA analysis

[1] Power grids and energy flexibility makes reference to all those elements that provide the flexibility needed to operate a power system with high shares of renewable power, and includes storage, demand management, and the power transmission and distribution grids.

The 100 million jobs figure is 15% more than under the Planned Energy Scenario and 72% greater than the present-day total. But the overall numbers do conceal significant changes in the composition of jobs. New jobs in transition-related technologies and sectors are expected to outweigh job losses in fossil fuels and nuclear energy.

Transition-related technologies

The evolution of employment in the energy sector as a whole depends not only on the deployment of renewable energy technologies, but on other factors as well. On the one hand, energy efficiency and system flexibility yield more jobs under the Transforming Energy Scenario than under the Planned Energy Scenario. On the other hand, the number of jobs in fossil fuel extraction and power plant operations will decline as the transition progresses under either scenario, challenging the workforce in this sector. This section provides a detailed breakdown of estimated jobs in renewables, followed by the jobs in energy efficiency, and power grids and energy flexibility.

Jobs in the renewable energy sector. The Transforming Energy Scenario leads to an increase of renewable energy jobs. Figure 2.3 presents the global evolution of renewable energy jobs, by technology, from 2017[2] to 2030 and 2050 for both the Planned Energy and Transforming Energy scenarios. The latter would yield close to 30 million renewable energy jobs by 2030 and 42 million by 2050. The 2050 estimate represents a 64% increase over the Planned Energy Scenario.

This is the workforce that will be required to install, operate and maintain the renewable energy capacities projected under the Transforming Energy Scenario. But this large workforce, with its manifold skills and occupational profiles, will not materialise automatically and a successful transition will depend on appropriate education and capacity building policies.

The projection cited above, as well as the detailed analysis behind it (IRENA, 2020a), is the linchpin of a successful matching of demand for, and supply of, skills. Estimates of how those jobs are likely to be distributed across segments of the value chain, and across economic sectors and occupational groups, can guide governments as they make policy for industrial development and capacity expansion. Energy sector policy makers should consult and co-ordinate closely with the renewable energy industry and with educational institutions.

For a subset of five renewable energy technologies[3], Figure 2.4 presents an example of this type of information, breaking down the jobs needed in 2050 into segments of the

[2] IRENA has been monitoring renewable energy jobs since 2011, producing an annual review (IRENA, 2019p) with updated results. These monitoring results have been used to calibrate the macroeconomic model for the year 2017. Once calibrated, the model allows for filling gaps in the monitoring procedure (technologies and countries without data), providing a full picture of initial renewable energy employment and its forecasted evolution in response to implementation of the energy transition roadmap.

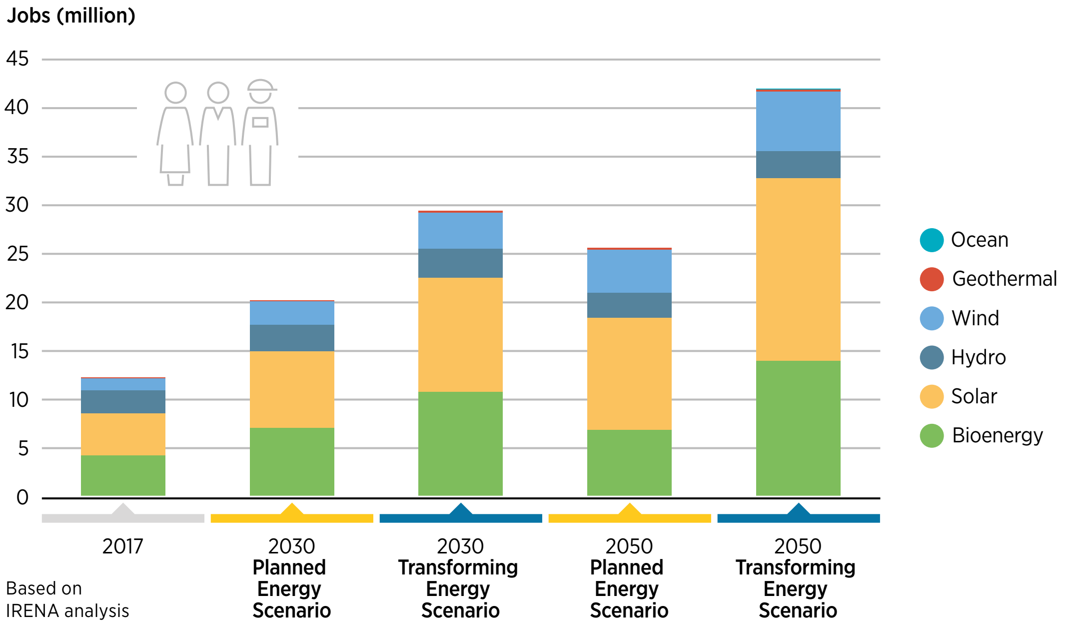
[3] The technologies included are solar photovoltaics (PV), solar water heaters (SWH), onshore wind, offshore wind and geothermal, representing a total of around 25 million jobs – about 59% of the total 42 million renewable energy jobs projected for 2050. These are the technologies for which the skill requirements are best known. The analysis draws from IRENA's work on leveraging local capacities (IRENA, forthcoming c, 2018c, 2017e, 2017f). The skill structure for additional technologies can be fleshed out as the leveraging analysis for those technologies becomes available.

value chain and broad occupational groups. Construction and installation dominate the first distribution with a 47% share, while workers and technicians dominate the second with a 77% share. Increasing the geographical granularity to focus on regional results (Chapter 4) affords additional insights into the value chain and skills distributions of the jobs needed to support the transition. Such data is a prerequisite for transition policies that budget increases in education and training, assess local strengths, and identify tasks and functions that can be successfully localised.

Jobs in energy efficiency: In 2050, energy efficiency could employ 21.3 million people. This is 3.7 million or 21% more jobs compared to the Planned Energy Scenario. Compared to the current-day situation, the Transforming Energy Scenario will more than double the number of jobs.

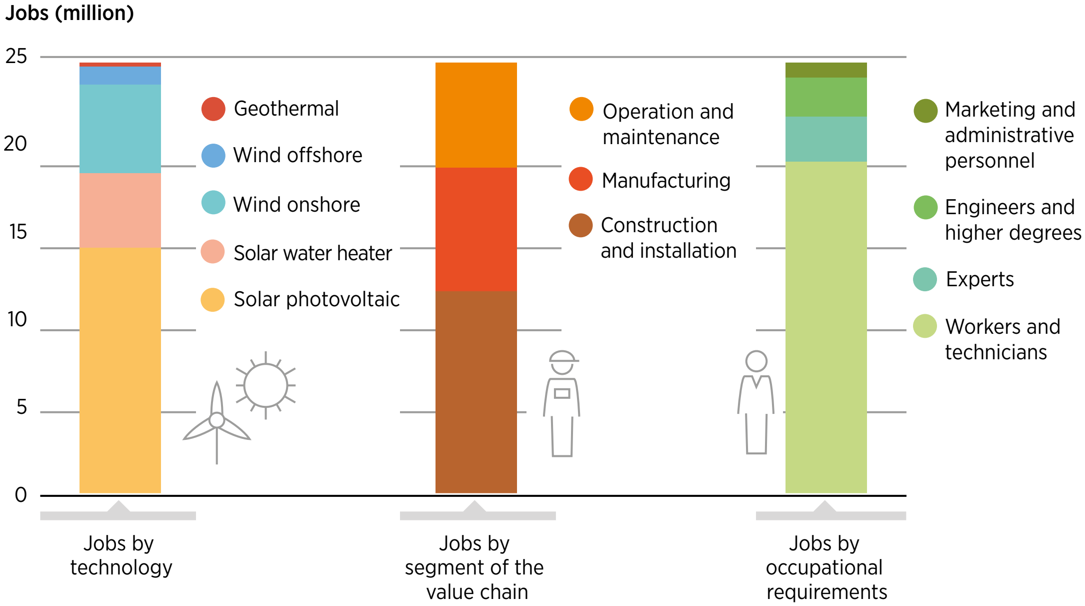
Jobs in power grids and energy flexibility: In 2050, 14.5 million people will be working in jobs related to power grids and energy flexibility in the Transforming Energy Scenario. This is 14% more than under the Planned Energy Scenario. Similar to energy efficiency jobs, the number of jobs will more than double compared to the current number of jobs.

Figure 2.3 Renewable energy jobs: Dominated by solar energy technology
Global renewable energy jobs for the Planned Energy Scenario and the Transforming Energy Scenario in 2017, 2030 and 2050



Based on IRENA analysis

Figure 2.4 **Deep-dive analysis: Majority of jobs will be created in construction and installation and for workers and technicians**
Jobs in selected renewable energy technologies by value chain segment and occupational category in 2050



Based on IRENA analysis

Jobs in conventional technologies

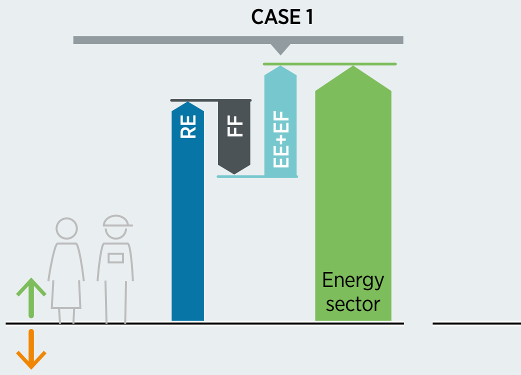
By contrast, the fossil fuel sector would shed jobs. A projected 22 million jobs under the Transforming Energy Scenario in 2050 would be 8 million below the 30 million under the Planned Energy Scenario, or 27% fewer. Compared to today's employment levels, the sector will lose over 6 million jobs.

Similarly, the nuclear energy sector will offer close to 0.15 million fewer jobs (a 23% reduction) than today and 0.3 million fewer (a 42% reduction) compared to the Planned Energy Scenario in 2050.

Before moving on to results for the economy as a whole, it is worth emphasising that job trends in the energy sector will vary with each region's degree of fossil fuel dependence, the ambitiousness of its transition plans, regional trade balances associated with sales of transition-related equipment and the relative weight of these factors in each region. Box 2.1 offers four hypothetical cases that illustrate different combinations of job gain and loss within parts of the energy sector, with different net outcomes. Regional insights are provided in Chapter 4 and in the Regional factsheets.

Box 2.1 DRIVERS OF GAINS AND LOSSES IN THE ENERGY SECTOR

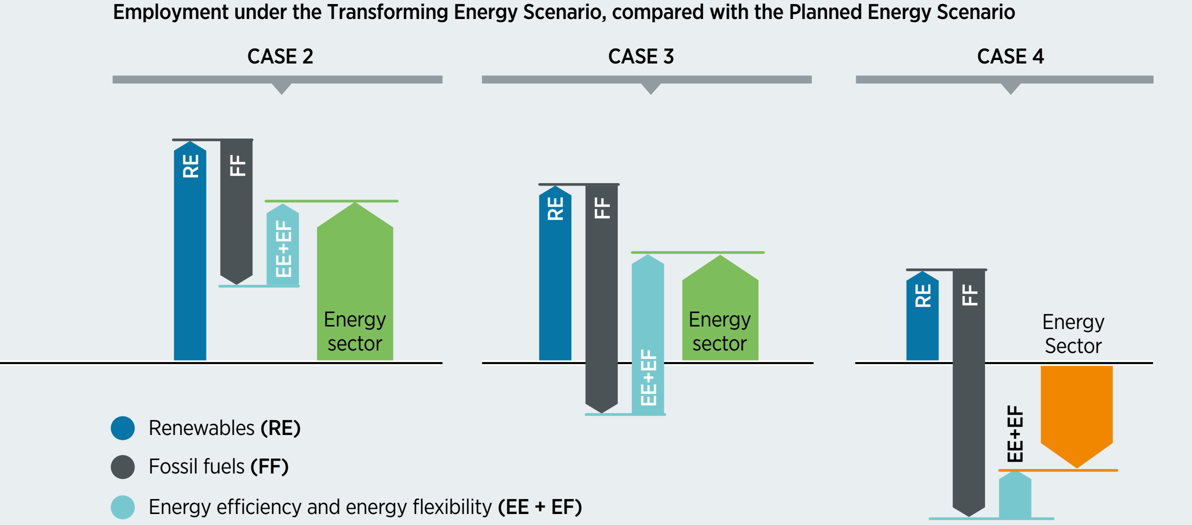
Although the Planned Energy Scenario leads to an overall increase in energy sector employment, jobs will be lost in some sub-sectors, namely those related to fossil fuels. The effects will vary depending on the factors at play in a given region. Figure 2.5 illustrates four cases in terms of the employment difference between the Transforming Energy Scenario and the Planned Energy Scenario, highlighting the underpinning factors and transition challenges.



Based on IRENA analysis

CASE 1. The increase in the number of jobs in the energy sector is higher than the increase in renewable energy jobs alone. This means that the increase in jobs in the other two technological transition pillars (energy efficiency and energy flexibility) is higher than the loss of jobs in fossil fuels. This is the most favourable situation for the energy sector, offering opportunities for people who lose their jobs in fossil fuels to find new ones in the energy sector. A smooth transition can be achieved by reducing the dependence on fossil fuels and implementing ambitious policies geared towards creating a large number of domestic jobs in renewables, efficiency and flexibility.

Figure 2.5 Energy sector job gains and losses: Four cases



CASE 2. The increase in the number of jobs in the energy sector is positive overall but lower than the increase of jobs in renewables, despite the loss of jobs in fossil fuels being lower than the increase in the number of jobs in renewables. A higher dependence of the regional economy on fossil fuels, a lower transition ambition, or a lower number of domestic transition-related jobs leads to less favourable results than in Case 1. Although the overall balance in the energy sector is still positive, there is a higher relative loss, increasing the challenges for those who lose their jobs to find new ones in the energy sector.

CASE 3. The increase in renewable energy jobs is smaller than the reduction in fossil fuel employment, but energy efficiency and flexibility still provide a positive balance in the energy sector. This gain in the energy sector manages to provide job opportunities for lost fossil fuel jobs, but the challenge for labour reallocation is greater than for Case 1 and Case 2 because of the higher relative weight of the lost jobs. Larger differences in requisite skills contribute to the challenge.

CASE 4. The number of lost jobs in fossil fuels is greater than the number gained in renewables, efficiency and flexibility, providing an overall negative balance within the energy sector. This is the most unfavourable and challenging case, which can arise in regions and countries that have 1) a labour market heavily dependent on fossil fuels, 2) low transition ambition, and 3) high dependence on imports of transition-related technologies. In this case, the energy sector does not provide job opportunities for all who lose their jobs in fossil fuels, requiring solutions for a just transition to be found outside the energy sector.

JOBS IN THE OVERALL ECONOMY

The switch to low-carbon technologies will certainly change the occupational and skills pattern in the energy sector. But beyond the energy sector, the Transforming Energy Scenario will also have economy-wide impacts. These cross-cutting effects come with job gains and losses resulting from multiple interactions within the economy driven by three sets of factors (Box 2.2 and Figure 2.6).

Figure 2.6 shows that global employment under the Transforming Energy Scenario is 0.15% higher (an additional 6.5 million jobs) than under the Planned Energy Scenario. As seen, the contribution of different drivers to the economy-wide jobs footprint varies. The investment driver typically exerts its influence at the outset of an installation, and thus makes an initial contribution. Across the entire time period considered, however, changes in consumer expenditure due to indirect and induced effects dominate economy-wide employment impacts.

Box 2.2 DRIVERS OF ECONOMY-WIDE JOBS AND GDP

The drivers of job and GDP gains and losses include changes in investment and trade, as well as induced and indirect effects:

CHANGES IN INVESTMENT

This driver concerns the net impact of overall investment in the economy and includes the effect of increasing transition-related investments (renew-ables, energy efficiency, energy flexibility, grids, etc.) as well as declining investments in conventional energy.

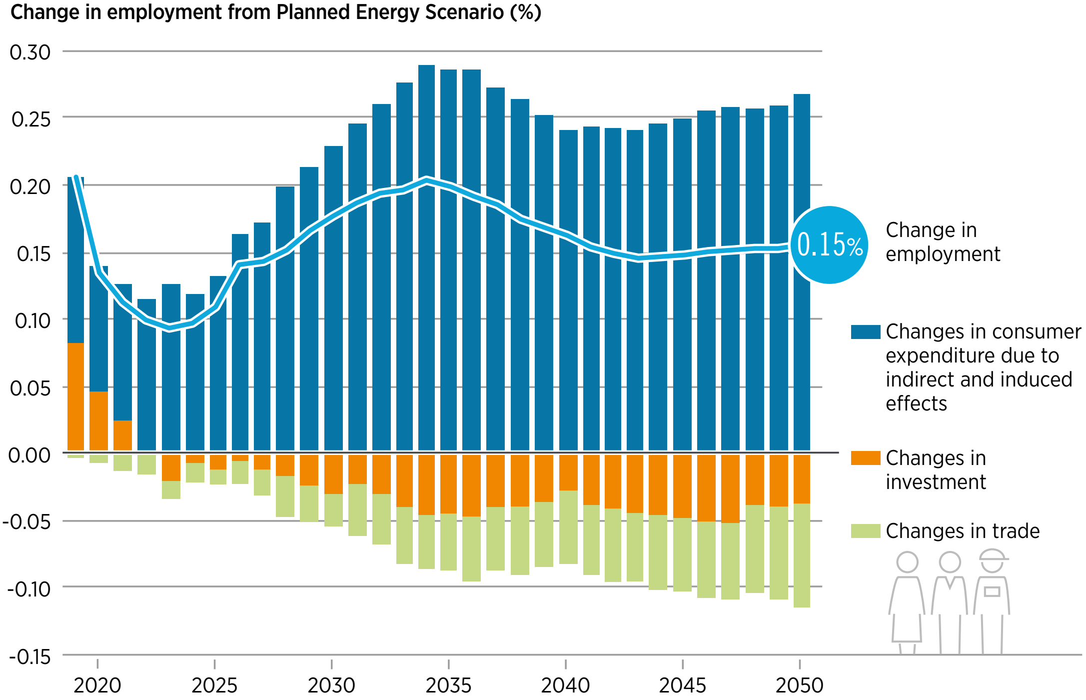
CHANGES IN TRADE

This driver includes the effects of both energy and non-energy trade. An increase in imports, or reduction in exports, has a negative impact on GDP, while a decrease in imports or increase in exports has the reverse effect.

INDUCED AND INDIRECT EFFECTS

This driver captures changes in consumer spending due to consumer price effects and fiscal policy. The driver also includes changes in economic activities due to supply chain impacts arising from payments to producers in the supply chain, and other effects associated with changes in employment levels or wages for existing employees.

Figure 2.6 Economy-wide jobs: Increase by 6.5 million
Difference in global economy-wide employment between the Transforming Energy and Planned Energy scenarios



Based on IRENA analysis

The impact of the Transforming Energy Scenario on jobs varies within the energy sector and has implications throughout the economy. This is illustrated in Figure 2.7 with the global increase in employment under that scenario relative to the Planned Energy Scenario at three different levels: in renewable energy, the energy sector as a whole and across the entire economy.

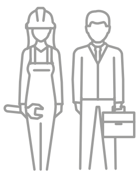
The energy sector gains 13.3 million jobs, which is lower than the 16.3 million jobs gained in renewables alone. While renewables, energy efficiency, and power grids and energy flexibility all gain jobs under the Transforming Energy Scenario, the remaining sub-sectors are hit especially hard by the transition. In this case the fossil fuels sub-sector is the clear loser within the energy sector (8.2 million jobs fewer than in the Planned Energy Scenario).

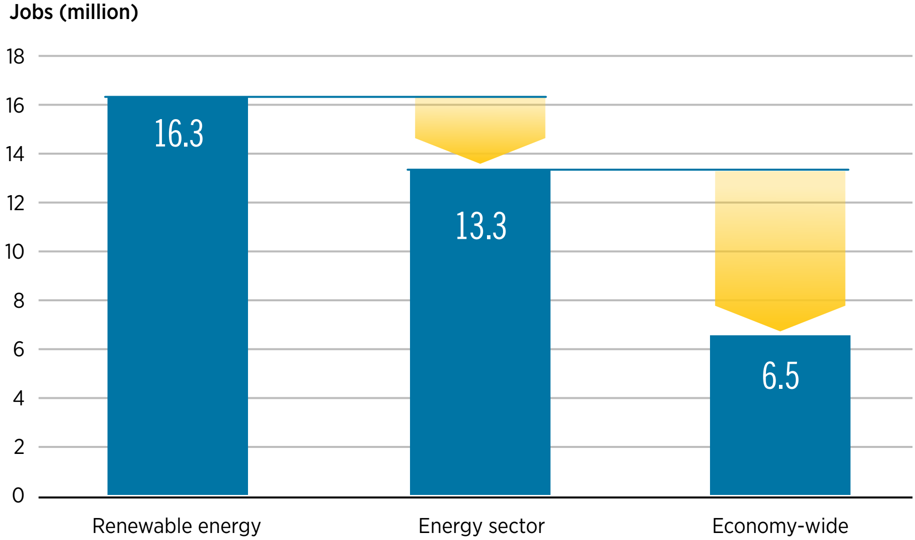
This is an understandable outcome of the transition, as fossil fuels and related technologies are expected to be phased out. Nonetheless, the socio-economic consequences of this phase-out, if not properly addressed, may become barriers to the transition. Awareness of this misalignment is already high in the energy sector, as evidenced by increased calls for just and inclusive transition policies.

Job gains in the energy sector (13.3 million) surpass the number of additional jobs economy-wide (6.6 million). This, too, is to be expected, given that the energy transition entails measures that directly affect the energy sector while affecting other parts of the economy less directly. Several dynamics produce these results, including how overall investment is distributed across sectors of the economy, sectoral job intensities, and how the transition drivers affect each sector. Another crucial factor is the ability and size of multipliers in the existing economic structure to support transition-related technologies.

What these results point to is the need for a holistic, just transition policy framework that looks beyond the energy sector since job loss can affect sectors other than fossil fuels.

Figure 2.7 Renewable energy, energy sector and overall economy
Global employment job differential in 2050 (increment of jobs from Planned Energy Scenario to Transforming Energy Scenario), by sector



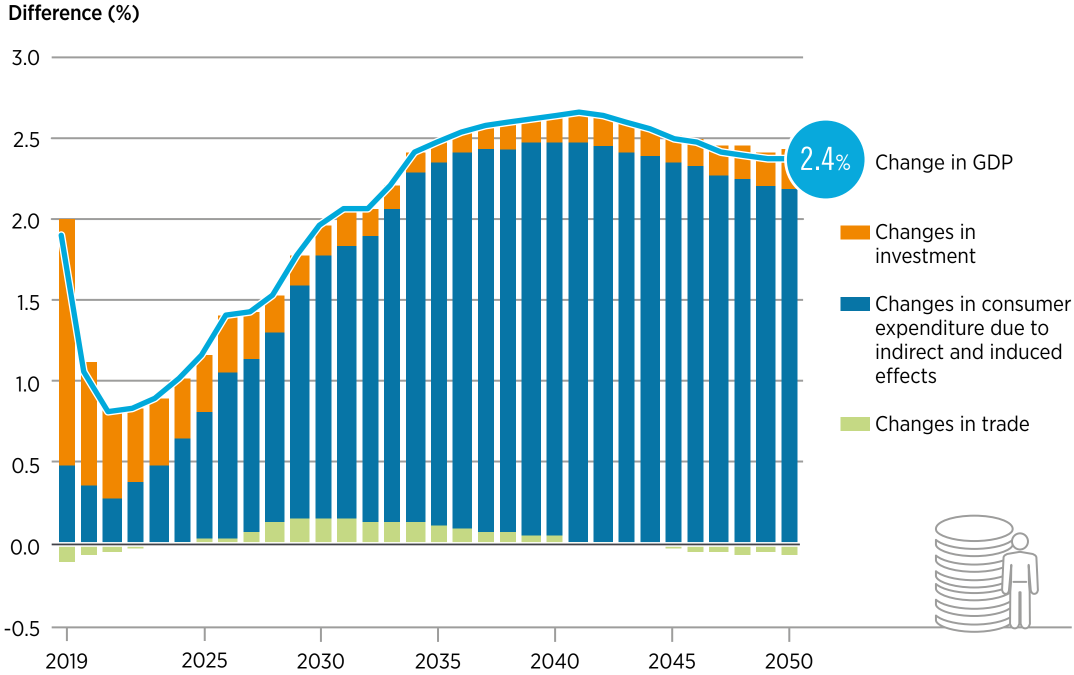


Based on IRENA analysis

2.2 Gross domestic product

GDP is the most commonly used indicator for income and growth. In line with earlier IRENA estimates (IRENA, 2019a), the Transforming Energy Scenario boosts global GDP in 2050 by 2.4% over the Planned Energy Scenario. The cumulative gain from 2019 to 2050 amounts to USD 98 trillion.[4] The gain is influenced by several drivers in the global economy and is illustrated in Figure 2.8. The investment driver contributes most heavily to the gain during the first years of the transition, remaining positive but with a relatively low impact thereafter. The trade driver makes marginal contributions to global GDP gains over the Planned Energy Scenario, given the intrinsic requirement of global trade being balanced in normal terms. The largest share of the positive global GDP results is explained by changes in consumer spending in response to changes in fiscal policy considered in this analysis.[5]

Figure 2.8 Transforming Energy Scenario will boost global GDP
Difference in global GDP between Transforming Energy Scenario and Planned Energy Scenario



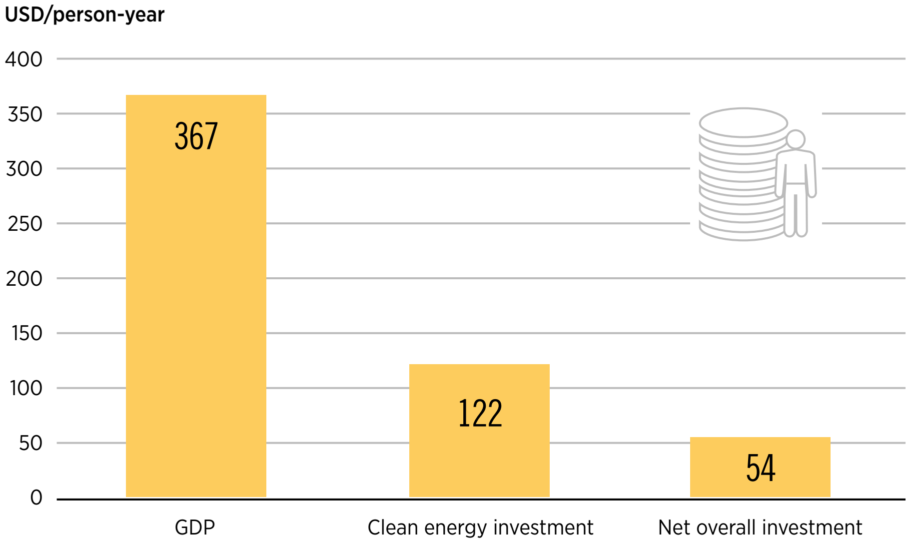
Based on IRENA analysis

[4] All U.S. dollar values in this chapter are 2015 constant values.

[5] Carbon taxation is in line with the Integrated Assessment Model and the 2˚C limit on global warming (IPPC, 2014). The applied revenue recycling policy applied in the analysis assumes government revenue neutrality by balancing the evolution of taxes linked to the transition (carbon taxation, oil royalties) with income taxes. The implications of the revenue recycling policy were discussed in the section on employment.

In per capita annual terms,[6] the difference in the gains realised under the two scenarios is USD 367/person-year. Figure 2.9 compares this per capita value with the net overall investment requirement[7] (USD 54/person-year) and the clean energy investment requirement (USD 122/person-year). The figure shows that additional investment together with appropriate policies, primarily in the clean energy sector, has significant economic effects, contrary to conventional beliefs that climate-related investments will adversely affect the economy.

Figure 2.9 Global per-capita GDP gains outstrip investment costs
Per capita annualised GDP values under the Transforming Energy Scenario, using average population for 2019-2050



Based on IRENA analysis

[6] Using the average world population for the years between 2019 and 2050.

[7] The additional investment needed in the overall energy sector is lower than the additional investment needed in the clean energy sector. This is due to the fact that the transformation of the energy sector under the Transforming Energy Scenario entails a reduction of investment in conventional technologies and greater investment in clean energy sector when compared with the Planned Energy Scenario.

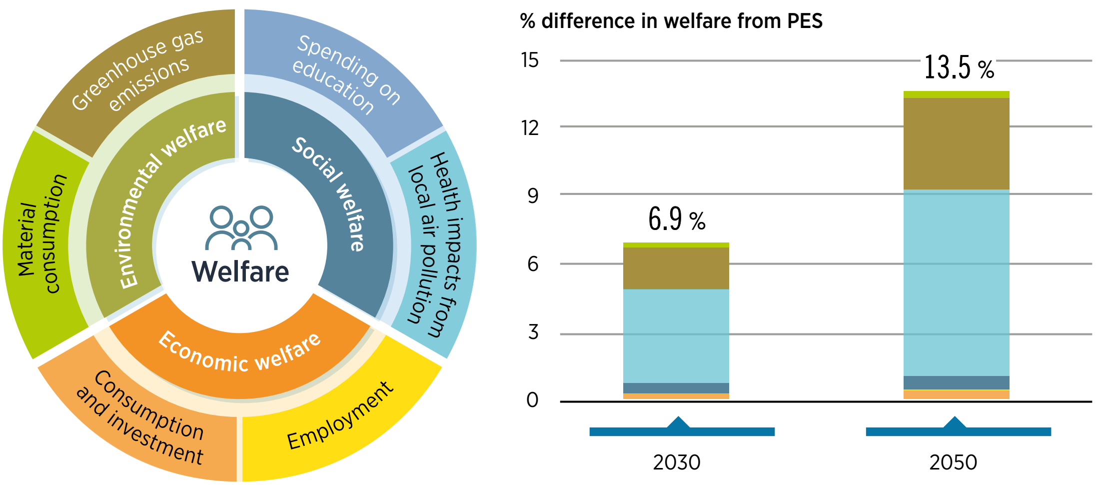
2.3 Welfare

Jobs and GDP growth, as described above, are the standard measures of socio-economic analysis. To address concerns that these indicators do not fully capture whether the quality of life improves due to the energy transition, this section presents a composite indicator that comes closer to measuring the multidimensional nature of welfare improvements (IRENA, 2016c).

The indicator includes economic, social and environmental dimensions aggregated from sub-indicators. Each indicator is derived from two sub-indicators. The economic dimension is obtained from household consumption and investment as well as employment. The social indicator consists of spending on education and health impacts from air pollution. The environmental indicator is made up of greenhouse gas emissions and consumption of materials. More detail is provided in Table 2.1.

As measured by this method, global welfare improves faster and further under the Transforming Energy Scenario than under the Planned Energy Scenario, surpassing it by 13.5% by 2050 (Figure 2.10). The social and environmental dimensions predominate, reflecting the significant improvements in health obtained by curbing air pollution and reducing greenhouse gas emissions.

Figure 2.10 Welfare gains: Influenced by health benefits and emission reduction
Global welfare indicator under the Transforming Energy Scenario in 2030 and 2050



Based on IRENA analysis

Box 2.3 STRUCTURE OF THE WELFARE INDICATOR

To construct the welfare indicator used in this analysis, results from the macroeconomic model are used to create six sub-indicators that inform three welfare dimensions (economic, social and environmental). Since each sub-indicator has its own units, the six are expressed in terms of the percentage difference between the Transforming Energy Scenario and the Planned Energy Scenario, then weighted equally and aggregated into the overall indicator.

Dimension	Sub-indicator	Detail	Units	Weight in aggregated indicator
Economic	Consumption plus investment	Sum of both household consumption and economy-wide investment (*i.e.*, capital formation) in each year and country	Constant 2015 USD	1/6
	Employment	Economy-wide employment in all the 43 economic sectors considered, in each year and country	Number of jobs	1/6
Social	Spending on education	Public and private spending on education, in each year and country	Constant 2015 USD	1/6
	Health impacts	Energy consumption in power generation and end use sectors (TJ) differentiated by fuel and multiplied by health externality (USD/TJ) for each fuel from IRENA analysis, in each year and country	Constant 2015 USD	1/6
Environ-mental	Greenhouse gas emissions	Cumulative greenhouse gas emissions (using the global value for the indicator in all countries). Cumulative values are used because they are the ones that relate to the associated externality (climate change).	Tonnes of CO_2 equivalent	1/6
	Consumption of materials	Cumulative use of materials excluding fossil fuels. Cumulative values are used because they are the ones that relate to the associat-ed externality in most cases (depletion of finite resources).	Gigatonnes	1/6

Adapted from IRENA, 2016c

2.4 Conclusion

The socio-economic footprint of the energy transition as quantified in the Transforming Energy Scenario conveys a positive message on a global scale. Jobs and GDP growth will be positive while welfare improves significantly (see Table 2.1 for key numbers). When examined at the country and regional levels, however, the socio-economic footprint will vary more or less widely from the global footprint, owing to the variety of socio-economic structures and their complex interactions with the energy transition. The complex challenges also call for local solutions. Likewise, the opportunities offered by the energy transition are unique for each region, as further explained in Chapter 4.

Table 2.1 A roadmap to 2050: Tracking key socioeconomic indicators of the global energy transformation

Global	2019	2030	2050
Population (thousands) region-wide	7 656 137	8 379 776	9 358 932
GDP (USD 2015)			
GDP (million): PES	83 643 985	117 717 477	214 272 530
GDP (million): TES	85 247 810	120 011 802	219 366 861
GDP changes (million): TES vs. PES	1 603 826	2 294 325	5 094 331
GDP changes (%): TES vs. PES	1.92%	1.95%	2.38%
Per capita GDP (thousand): PES	10.93	14.05	22.89
Per capital GDP (thousand): TES	11.13	14.32	23.44
Employment			
Economy-wide employment (thousands)			
Employment: PES	3 714 168	4 051 588	4 238 092
Employment: TES	3 721 777	4 058 720	4 244 626
Employment changes: TES vs. PES	7 608.94	7 132	6 534
Employment changes (%): TES vs. PES	0.20%	0.18%	0.15%

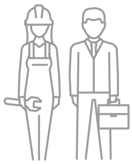
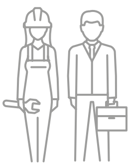


Table 2.1 A roadmap to 2050: Tracking key socioeconomic indicators of the global energy transformation (continued)

Global	2017	2030 (PES)	2030 (TES)	2050 (PES)	2050 (TES)
Energy sector jobs (thousands)					
Nuclear power	560	770	696	739	430
Fossil fuels	28 085	33 255	29 133	29 878	21 680
Renewables	12 288	20 306	29 543	25 578	41 902
Energy efficiency	9 507	20 283	29 189	17 561	21 265
Energy flexibility & grid	7,439	11 507	12 078	12 721	14 494
Total	**57 879**	**86 121**	**100 640**	**86 478**	**99 771**
Energy jobs in economy-wide employment (%)		2.13%	2.48%	2.04%	2.35%
Renewable Energy Jobs (thousands)					
Bioenergy	4 371	7 154	10 890	6 998	14 090
Solar	4 286	7 916	11 717	11 501	18 698
Hydropower	2 389	2 747	3 013	2 569	2 759
Wind	1 160	2 374	3 744	4 355	6 057
Geothermal	80	113	156	150	238
Ocean	1	2	25	4	60
Total	**12 288**	**20 306**	**29 543**	**25 578**	**41 902**
Renewable energy jobs in energy-sector employment (%)		23.58%	29.36%	29.58%	42.00%
Job differential in 2050 (thousands)					
Economy-wide					6 534
Changes in conventional energy (A)					-8 507
Changes in transition related technologies (B)					21 801
Net energy sector jobs (A+B)					**13 294**



Technology jobs (thousands)		Segment value chain (thousands)		Occupational requirements (thousands)	
Solar PV	14 132	Construction & installation	11 639	Workers & technicians	19 044
Solar water heaters (SWH)	4 249	Manufacturing	7 061	Experts	2 541
Onshore wind	5 048	O&M	5 976	Engineers & higher degrees	2 246
Offshore wind	1 009	Biofuel supply	-	Marketing and administrative	846
Geothermal	238				
Total	**24 676**		**24 676**		**24 676**

Welfare improvement (%): TES vs. PES **Indicator/year**	**2030**	**2050**
Economic	0.34	0.49
Social	4.53	8.70
Environmental	2.03	4.29
Total	**6.9**	**13.5**

REGIONAL ENERGY TRANSFORMATIONS: TECHNO-ECONOMIC CONTEXT

03

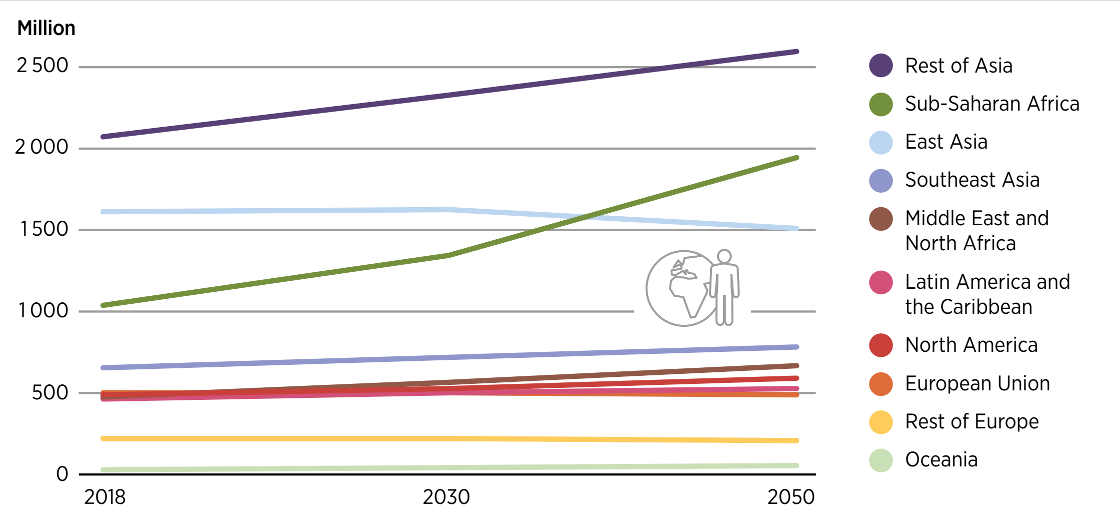
This chapter provides a regional perspective on the implications of the energy transformation for ten broad regions spanning the globe. **While there may be a single global climate objective, different energy transformation pathways need to be considered and solutions tailored to fit regional circumstances.**

These regions were defined based on geographical grouping, without consideration of socio-economic, political or cultural aspects. Any regional split tends to be somewhat arbitrary and could hide important differences among countries that affect the implications of the energy transformation in each case. Even so, examining IRENA's energy transformation results at the regional level can offer valuable insights. As the sections that follow demonstrate, important distinctions exist between regions.

3.1 Context and characteristics

POPULATION

Figure 3.1 World population growth: From 7.5 billion today to over 9.7 billion by 2050
Expected population trends from 2018 to 2050



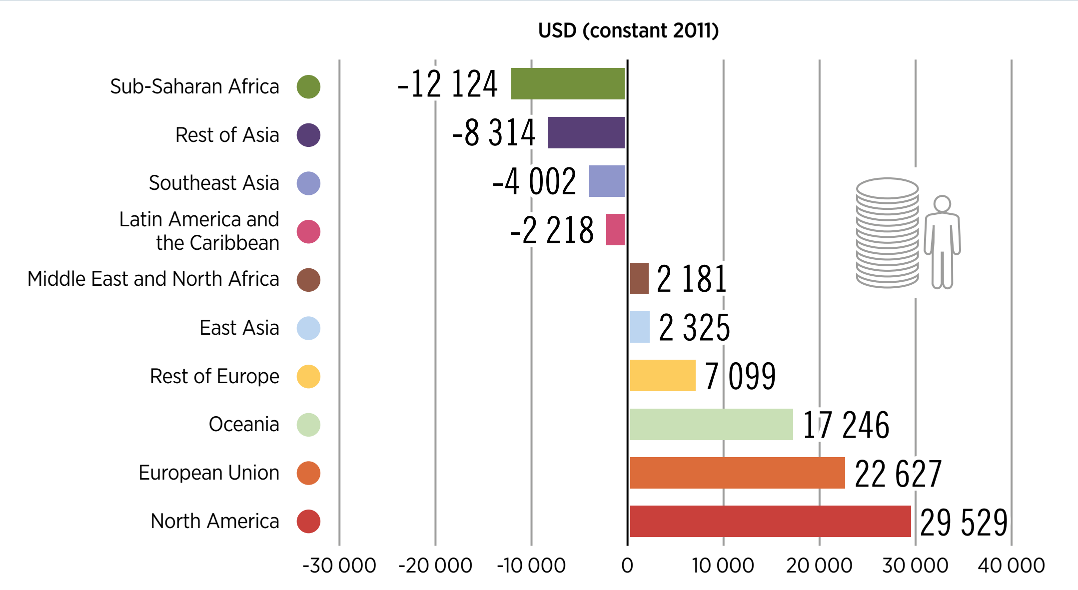
IRENA anlaysis based on E3ME.

Note: Oceania including PNG.

Most growth is expected in the Rest of Asia and in Sub-Saharan Africa. Small growth is expected in Southeast Asia, the Middle East and North Africa, Latin America and the Caribbean, North America and Oceania, whereas East Asia, the EU and the Rest of Europe show declining numbers.

GDP

Figure 3.2 Uneven wealth distribution among regions
GDP PPP per capita, deviation from global average, in 2018

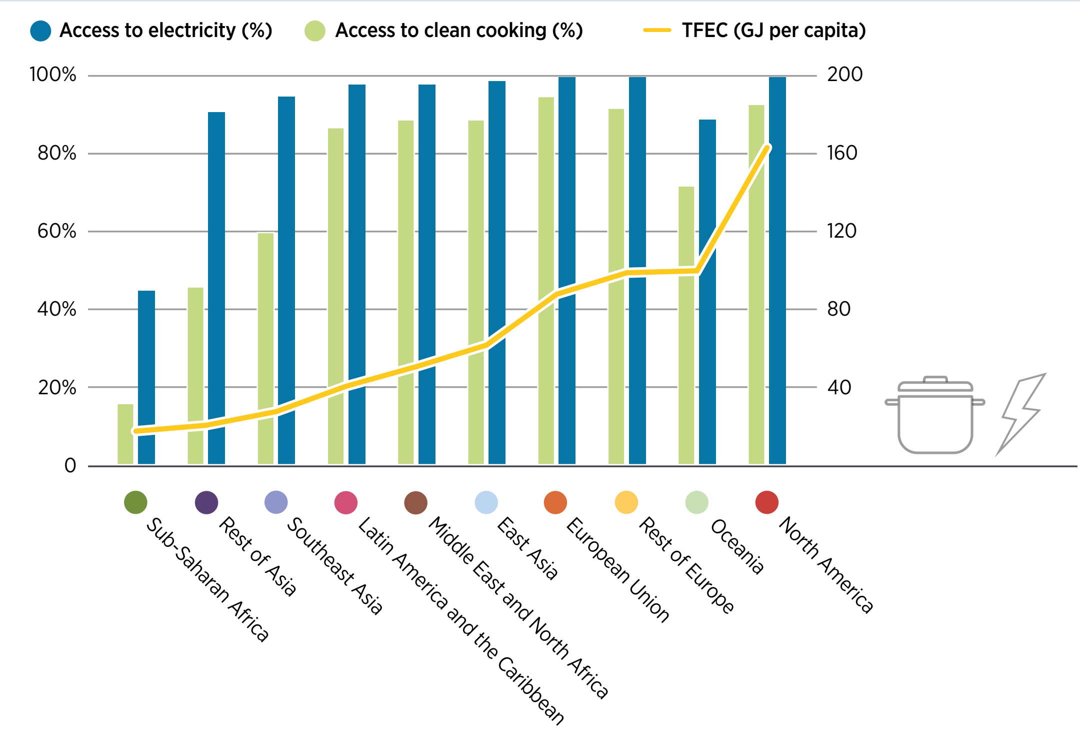


Note: Analysis based on 2018 values (World Bank Group, 2019a).

Distribution of wealth is unequal. In North America, the EU and Oceania, per capita GDP is well above the global average, whereas Southeast Asia, the Rest of Asia and Sub-Saharan Africa rank at the bottom. The contrast is more relevant in the face of demographics, as 78% of the population growth is expected to come from the poorest regions.

ENERGY CONSUMPTION AND ACCESS TO ELECTRICITY AND CLEAN COOKING FUELS

Figure 3.3 Energy consumption per capita: Rising in step with wealth and access
Energy consumption per capita and access to clean cooking and electricity

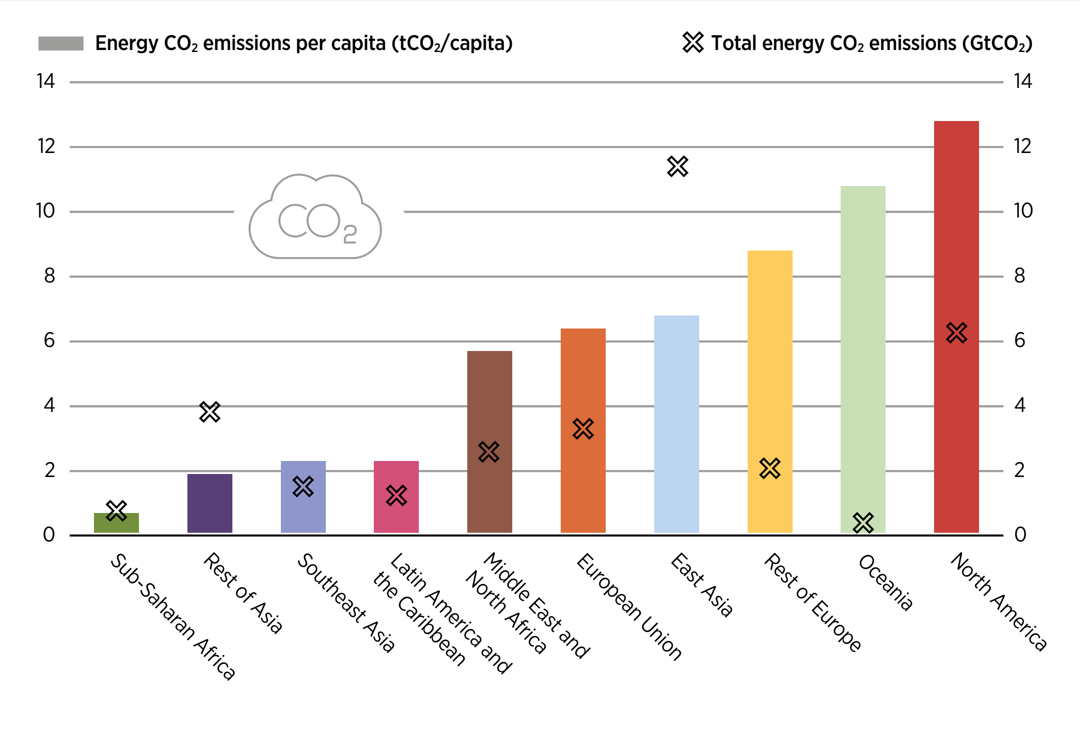


Note: Access to electricity, 2017 values (World Bank Group, 2019b), access to clean cooking, 2016 values (World Bank Group, 2019c), TFEC, 2017 values (IEA, 2019b).

Richer regions display the highest energy consumption per capita, and the three poorest regions the lowest. Similar patterns can be seen for access to clean cooking fuels and electricity, although most regions display electricity access rates above 90%. The notable exception is Sub-Saharan Africa, where electricity access is only 45%, well below the world average of 89%.

CO_2 EMISSIONS IN THE ENERGY SECTOR

Figure 3.4 Energy-related CO_2 emissions: current level in regions
Energy-related CO_2 emissions, per capita and total, in 2018

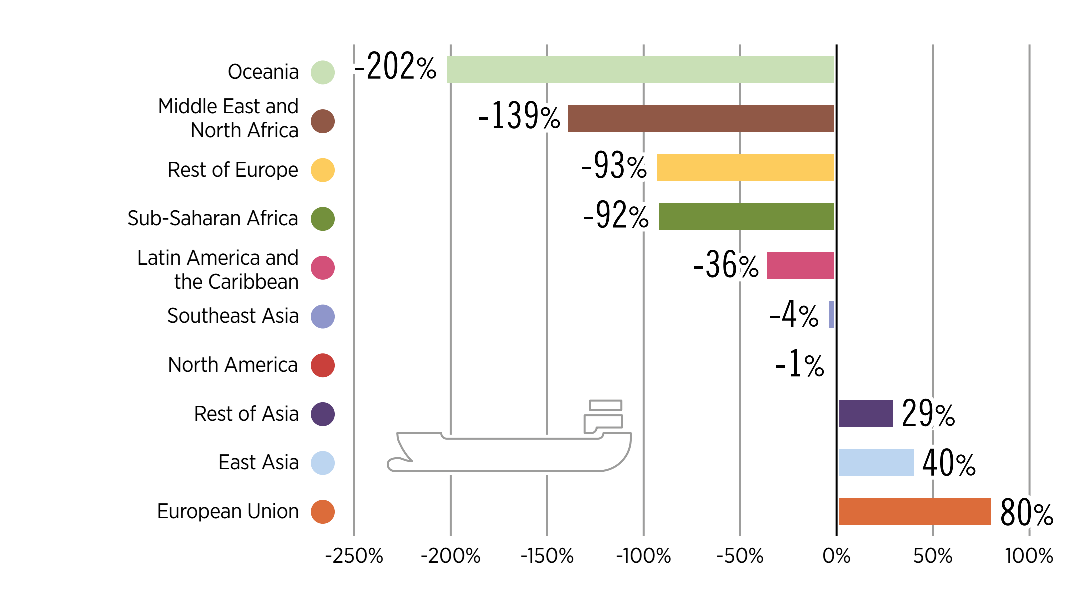


Note: Analysis based on 2018 values (Global Carbon Atlas, 2019).

Low access to energy results in low emissions per capita. Total emissions are highly influenced by total population. Some regions with rather low emissions per capita become prominent in total emissions because of their large populations.

FOSSIL FUEL DEPENDENCE

Figure 3.5 Fossil fuel imports and exports: Net balance by region
Energy security measured as the proportion of net imports of fossil fuels in total primary fossil fuel energy supply, in 2017

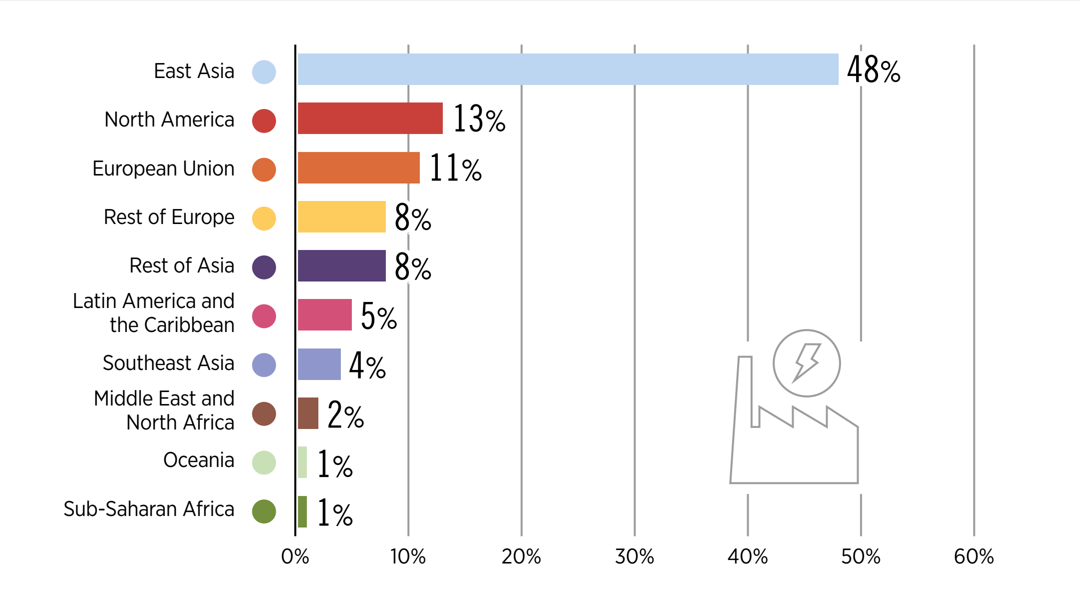


Note: Analysis based on 2017 values (IEA, 2019b).

Most regions are currently net exporters of fossil fuels (negative bars above), with Southeast Asia and North America practically at zero. In a carbon-constrained world, these net exporters would stand to lose if they are not prepared for the drop in global fossil fuel demand. Conversely, the Rest of Asia, East Asia and the EU could benefit greatly from reducing their external dependence on fossil fuels.

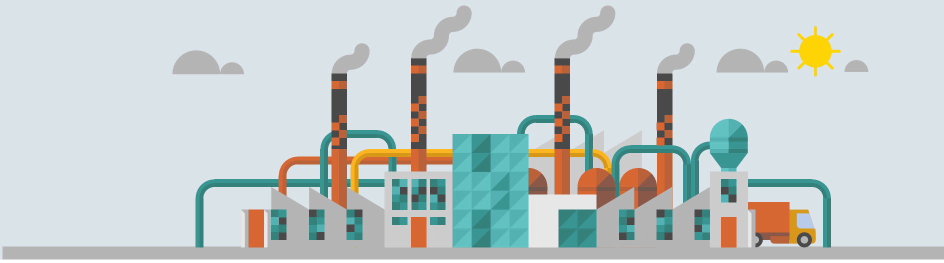
ENERGY-INTENSIVE INDUSTRIES

Figure 3.6 Energy-intensive industries: High demand concentrated in East Asia
Regional share in global energy consumption of energy-intensive industries, in 2017



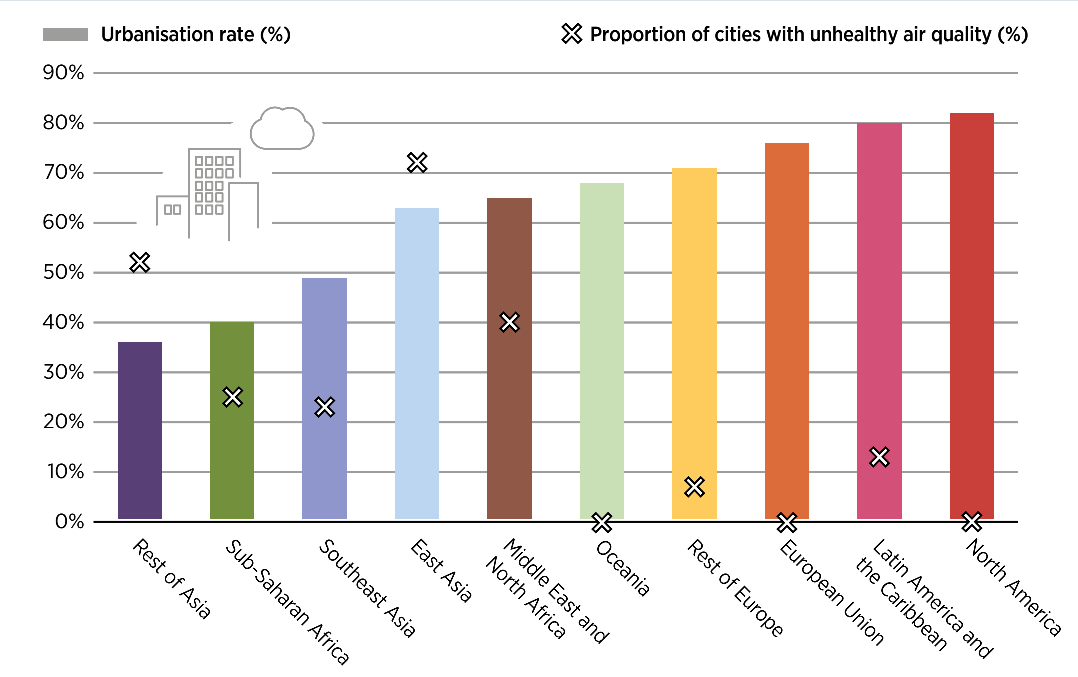
Note: Analysis based on 2017 values considering iron and steel, chemical and petrochemical, non-metallic minerals, non-ferrous metals, food, tobacco and paper industries (IEA, 2019b).

East Asia concentrates almost 50% of the global energy demand in energy-intensive industries (such as iron and steel, chemical and petrochemical, non-ferrous metals and non-metallic minerals). These industries correspond to an important share of global greenhouse gas emissions and are among the most challenging to decarbonise.



URBANISATION AND URBAN AIR QUALITY

Figure 3.7 Urban air quality: A major concern in fast-growing cities
Urbanisation and urban air quality

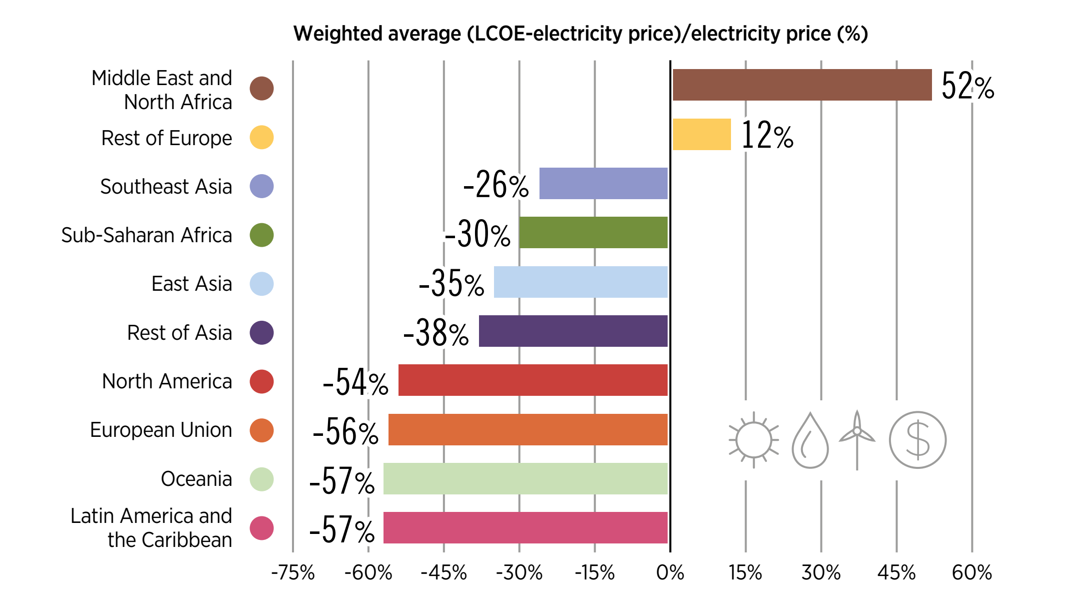


Note: Urbanisation, 2018 values (World Bank Group, 2019d), air quality (based on PM 2.5 concentration), 2016 and 2017 values (WHO, 2019).

In all but three regions (the Rest of Asia, Sub-Saharan Africa and Southeast Asia), more than 60% of the population lives in cities. This makes urban air quality a major concern. With expanding populations and urbanisation rates, a shift to renewables would help curb the most critical instances of urban air pollution, improving health conditions and quality of life.

COST-COMPETITIVENESS

Figure 3.8 Renewable electricity: Cheaper than average electricity price in most regions
Renewable electricity costs compared to electricity prices



Note: Costs denote 2018 values (IRENA, 2019i), electricity prices denote 2019 values (GlobalPetrolPrices, 2019).

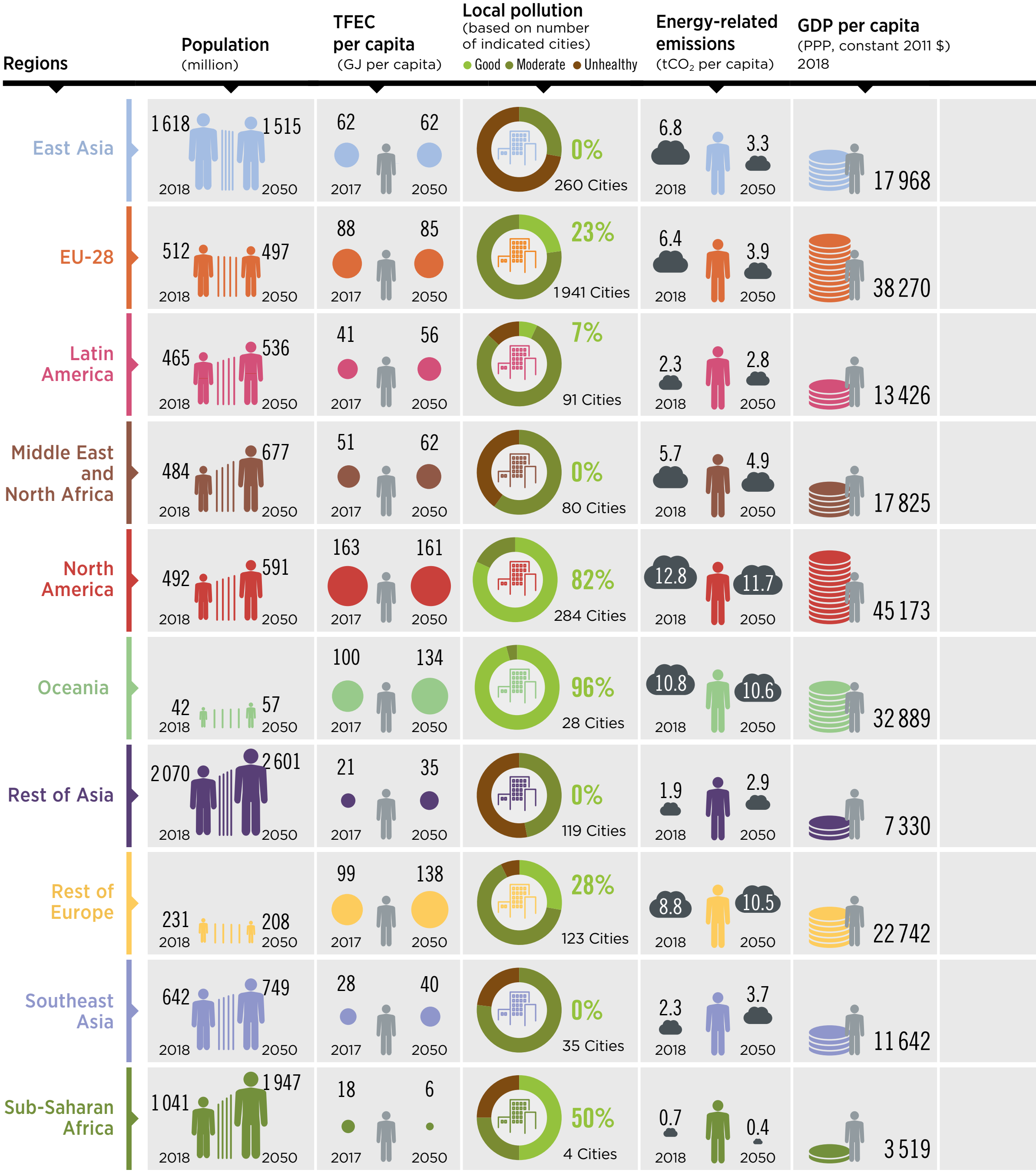
Renewable electricity costs are higher than electricity prices, on average, in only 2 of the 10 regions (the Middle East and North Africa region and the Rest of Europe). In all other regions, renewable costs are at least 20% lower than current electricity prices. This shows the potential for renewables to reduce prices of electricity.

3.2 Priorities and drivers

Figure 3.9 outlines key indicators showing the status of the energy transition in each region. The indicators reveal how each region has drivers for embracing the transformation, ranging from energy security, to emissions reductions and better air quality, to universalisation of energy access and economic development. This section provides more detail about the characteristics of three clusters of regions and some of the measures, technologies and changes that are needed to accelerate the energy transformation.

Figure 3.9 Planned Energy Scenario: Different prospects for each region

Status and key indicators for the energy transition in different regions in the Planned Energy Scenario



Note: PES based on IRENA; population, IRENA analysis based on E3ME (Oceania including PNG); TFEC, 2017 values (IEA, 2019b); local pollution (based on PM 2.5 concentration), 2016/2017 values (WHO, 2019); emissions, 2018 values (Global Carbon Atlas, 2019); GDP PPP (World Bank Group, 2019a); access to electricity, 2017 values (World Bank Group, 2019b), access to clean cooking, 2016 values (World Bank Group, 2019c); LCOE, 2018 values (IRENA, 2019i), electricity

Energy access (% population with access to **Clean Cooking** and **Electricity**)		Renewables Competitiveness (LCOE - price)/price — Non-competitive / Competitive	Fossil fuel dependence	Resource availability (Generation in PES by 2050 over technical potential)				
89%	99%		high	4.6%	13.5%	10.3%	9.4%	68.4%
95%	100%		very high	3.0%	1.7%	2.8%	11.4%	19.8%
87%	98%		low	0.7%	1.3%	0.7%	4.8%	44.4%
89%	98%		very low	0.1%	1.4%	0.4%	3.9%	37.5%
93%	100%		medium	2.4%	4.5%	0.5%	1.8%	55.5%
72%	89%		very low	0.2%	6.7%	0.1%	2.9%	24.3%
46%	91%		high	2.3%	2.3%	2.3%	8.1%	26.0%
92%	100%		low	0.1%	0.5%	0.0%	2.0%	19.5%
60%	95%		medium	4.3%	32.8%	0.2%	11.8%	44.7%
16%	45%		low	0.1%	2.0%	0.1%	2.4%	11.8%

prices, 2019 values (GlobalPetrolPrices, 2019); fossil fuel dependence (proportion of net imports of fossil fuels in TPES), 2017 values (IEA, 2019b); resource availability: solar PV (Korfiati et al., 2016), geothermal (in this case, a "realistic" potential is considered, see (Deng et al., 2015)), wind (Bosh, Staffel, hawkes, 2018, 2017), biomass (IRENA, 2014), hydro (Hydropower & Dams-World Atlas, 2014).

Countries have been grouped in three main clusters, reflecting similar drivers for the transformation of the energy system.

CLUSTER A: NORTH AMERICA, EU-28, REST OF EUROPE, OCEANIA

Cluster A generally consists of high-income countries that expect limited, or declining, population growth until 2050. Energy consumption per capita is generally well above the global average. Under the Planned Energy Scenario, energy-related CO_2 emissions in the regions will rise over the next three decades except in the EU-28. By 2050, emissions are expected to double in Oceania. In North America, despite an expected 10% increase in overall energy demand until 2050, emissions are expected to remain flat. Conversely, energy-related CO_2 emissions in the EU-28 will fall by one-third by 2050 compared to current levels. However, the Transforming Energy Scenario requires that these large emissions-contributing regions deploy solutions to rapidly reduce their emissions by at least 80% compared to current levels.

The key drivers for the transformation of the energy system in these regions include:

- ➜ **Enhancing energy security:** There is a need to diversify the energy supply away from fossil fuels to competitive renewable sources.
- ➜ **Competitiveness of the economy and leadership in innovation:** The deployment of renewable energy technologies offers a strong business case for investors and could foster a green economy and reinforce these countries as clean technology leaders.
- ➜ **Reducing emissions:** Many of these countries are responsible for large amounts of historical emissions and should lead in reducing emissions in the years to come. Renewable energy and energy efficiency are the key tools to achieve this aim.

CLUSTER B: MIDDLE EAST AND NORTH AFRICA (MENA) AND EAST ASIA

Cluster B generally consists of middle-income countries that have experienced robust growth in recent decades. Final energy consumption per capita in these regions is slightly above the global average and is expected to grow slightly by 2050. Currently these regions as a whole contribute a large share of global CO_2 emissions, driven largely by East Asia. As a result of enabling policies and measures, energy-related CO_2 emissions in East Asia are expected to fall by more than half in the next three decades, led by action in China. In the MENA region, energy-related CO_2 emissions are expected to continue to rise in the next three decades, due mainly to rapid population growth and to low energy prices resulting from subsidies for fossil fuels.

Plummeting oil demand and prices as experienced in early 2020s could result in profound economic consequences for the countries that are major exporters of fossil fuels.

The key drivers for the transformation of the energy system in these regions include:

- ➜ **Reducing emissions and improving air quality:** An effective transformation of the energy mix from one dominated by fossil fuel sources to one dominated by renewable energy sources would reduce pollution levels, vastly improving urban air quality, and enhance overall environmental conditions, thereby reducing health damages.
- ➜ **Diversifying the economy:** Supporting and leveraging clean energy technology, including new enabling technologies such hydrogen and batteries, would drive economic development. The current oil price volatility takes place against the backdrop of a rapidly changing energy system that is moving us towards a more sustainable and equitable energy world. Given the long-term planning horizons involved and the momentum that currently exists in the energy transformation, it is unlikely to be interrupted by short term volatility in fossil fuel price.
- ➜ **Enhancing consumer awareness and engagement:** Promoting social initiatives and actions (including demand-side measures) could increase the pace of the energy transition in the region by improving energy efficiency.

CLUSTER C: SUB-SAHARAN AFRICA, SOUTHEAST ASIA, REST OF ASIA, AND LATIN AMERICA AND THE CARIBBEAN

Cluster C generally consists of middle- to low-income developing countries that have experienced mixed growth in recent decades. Final energy consumption per capita in these regions is generally below the global average. In the next three decades, modern energy consumption per capita (which excludes traditional uses of bioenergy) is expected to increase in most of these regions. These regions have made remarkable progress in providing electricity access in the last decade; however, gaps remain in achieving full electrification in some countries. Access to clean cooking fuels is an area of significant concern for some of the countries. In the Planned Energy Scenario, energy-related CO_2 emissions trends vary among regions. Emissions are expected to nearly double in Southeast Asia and the Rest of Asia, and to increase slightly in Sub-Saharan Africa and Latin America and the Caribbean. Air pollution remains a major problem, mainly in urban areas in these regions, and will only worsen with increased reliance on fossil fuels.

The key drivers for the transformation of the energy system in these regions include:

- **Universalisation of access and infrastructure improvement:** A key priority is to provide energy service needs for the existing and growing population. Scaling up renewable energy deployment would be a business opportunity as well as a strategic option to increase energy access and the resilience of the energy system.
- **Reducing emissions and improving air quality:** Shifting away from fossil fuels and traditional uses of bioenergy to modern renewable energy sources would improve local air quality while reducing carbon emissions.
- **Economic development and cost-competitiveness of renewables:** Maximising use of the huge, diverse, dispersed and competitive renewable energy potential in the regions would bring energy system costs down while adding value to the economy and creating jobs.

3.3 IRENA's transformative pathway to 2050

Figure 3.10 outlines key indicators that show how each region can move from where it is today to where it would need to be in 2030 and 2050, as detailed in the Transforming Energy Scenario. The indicators show that significant acceleration is needed across a range of sectors and technologies, including deeper electrification of end-use sectors and higher shares of renewables.

Looking at the regional findings, some trends can be identified. In terms of energy demand growth, while energy use does not increase in Europe, the MENA region and North America, the other regions see some growth.

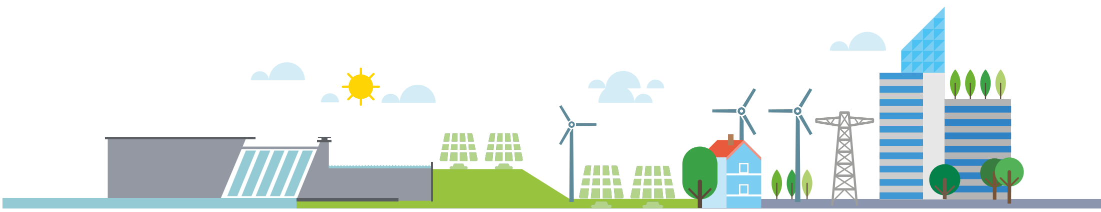


Figure 3.10 **Global energy decarbonisation: Different regional transition paths**

Regional indicators including emissions, energy demand and electrification shares in the Transforming Energy Scenario

Transforming Energy Scenario (TES)

Regions	Emissions: Energy-related CO_2 ($Gt\ CO_2/yr$) 2017	2030	2050	Electrification in end-use consumption (% in TFEC) 2017	2030	2050
East Asia	11.2 Gt CO_2/yr	8.4 Gt CO_2/yr	2.2 Gt CO_2/yr	25%	37%	58%
European Union	3.4 Gt CO_2/yr	1.9 Gt CO_2/yr	0.6 Gt CO_2/yr	22%	30%	49%
Latin America and the Caribbean	1.2 Gt CO_2/yr	1.0 Gt CO_2/yr	0.6 Gt CO_2/yr	18%	26%	39%
Middle East and North Africa	2.5 Gt CO_2/yr	2.0 Gt CO_2/yr	1.1 Gt CO_2/yr	19%	20%	38%
North America	6.2 Gt CO_2/yr	3.7 Gt CO_2/yr	1.4 Gt CO_2/yr	20%	28%	52%
Oceania	0.4 Gt CO_2/yr	0.4 Gt CO_2/yr	0.1 Gt CO_2/yr	23%	22%	45%
Rest of Asia	3.5 Gt CO_2/yr	3.8 Gt CO_2/yr	2.0 Gt CO_2/yr	18%	26%	47%
Rest of Europe	2.0 Gt CO_2/yr	1.6 Gt CO_2/yr	0.7 Gt CO_2/yr	18%	23%	38%
Southeast Asia	1.4 Gt CO_2/yr	1.6 Gt CO_2/yr	0.8 Gt CO_2/yr	18%	20%	42%
Sub-Saharan Africa	0.8 Gt CO_2/yr	0.6 Gt CO_2/yr	0.3 Gt CO_2/yr	7%	23%	48%

Note: TES based on IRENA analysis, 2017 values based on Global Carbon Atlas (2019), IEA (2019b).

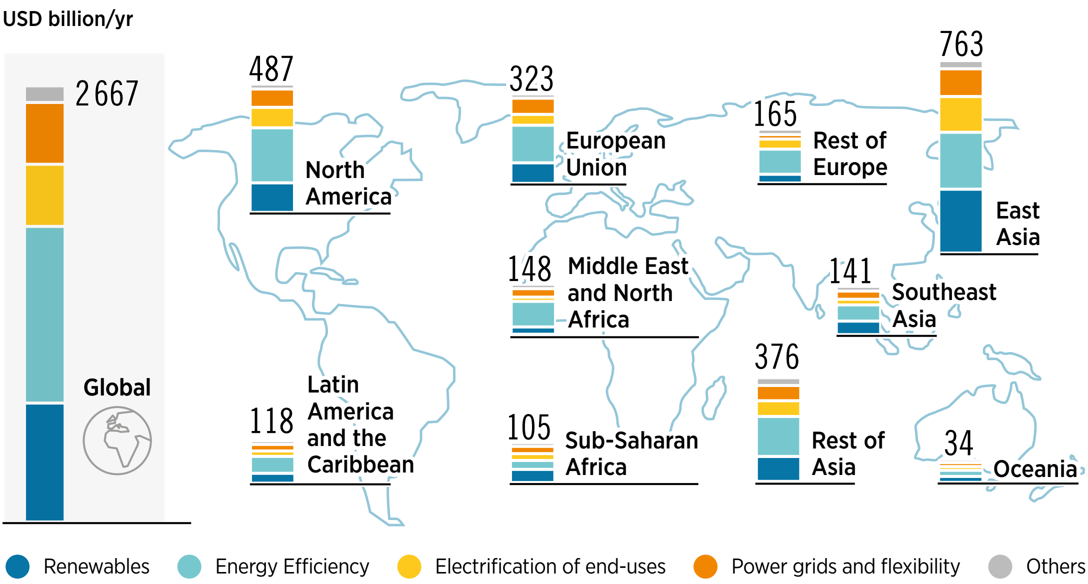
	Renewable Energy share in TPES (%)			Renewable Energy share in Power (%)		
	2017	2030	2050	2017	2030	2050
East Asia	7%	27%	65%	23%	60%	90%
European Union	15%	39%	71%	31%	55%	86%
Latin America and the Caribbean	30%	53%	73%	65%	85%	93%
Middle East and North Africa	1%	9%	26%	3%	27%	53%
North America	10%	30%	67%	23%	60%	85%
Oceania	10%	39%	85%	25%	66%	93%
Rest of Asia	8%	27%	58%	18%	52%	81%
Rest of Europe	6%	19%	54%	27%	42%	82%
Southeast Asia	13%	41%	75%	20%	53%	85%
Sub-Saharan Africa	7%	43%	89%	26%	67%	95%

The highest shares of renewable energy in total primary energy supply in 2030 would be reached by Latin America and the Caribbean, at 53%, followed by Sub-Saharan Africa at 43%. The EU would be at 31%. In contrast, the MENA region would have the lowest share at just 9%. However, by 2050 regional developments would be different, with the highest shares of renewables in TPES reached in Sub-Saharan Africa and Oceania, at levels above 80%, followed by Southeast Asia, Latin America and the Caribbean, and the EU above 70%. As in 2030, the MENA region would still have the lowest share at just 26% in 2050.

Similarly, electrification would have varying growth trends across the regions. The share of electricity consumption in final energy use in 2050 is the highest in East Asia at 58%, led by China. The Rest of Asia, North America and the EU have shares around 50%. Lower shares, at around 40%, occur in the MENA region, Southeast Asia, Latin America and the Caribbean, and the Rest of Europe.

The levels of investment in renewable energy needed to implement the Transforming Energy Scenario vary greatly by region and are not necessarily correlated with current shares of renewables. The main driver for investment levels in a region is generally population, followed by income level. The highest level of average annual clean energy investments over the period to 2050 will be seen in East Asia followed by North America, the Rest of Asia and the EU (Figure 3.11 and Table 3.1).

Figure 3.11 Transforming Energy Scenario: Varying investment needs by region
Annual investments in the energy transformation by region through 2050



Source: IRENA (2019q)

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Table 3.1 Annual investments in the Transforming Energy Scenario by region through 2050 (USD billion/yr)

	Renewables	Energy efficiency	Electrification of heat and transport	Power grids and flexibility	Others[a]	Total
East Asia	268	229	139	105	22	**763**
European Union	82	147	33	56	5	**323**
Latin America	31	59	10	15	3	**118**
Middle East and North Africa	18	96	5	23	6	**148**
North America	119	221	74	65	8	**487**
Oceania	13	13	3	4	1	**34**
Rest of Asia	93	157	54	52	20	**376**
Rest of Europe	25	94	30	6	10	**165**
Southeast Asia	45	56	11	22	7	**141**
Sub-Sahara Africa	43	25	16	18	3	**105**
Global	**735**	**1 099**	**374**	**372**	**86**	**2 667**

Source: IRENA (2019q)

a. Electrolysers for hydrogen production, biofuel supply, and carbon capture and storage combined with improved materials for industry.

3.4 Key actions

This report makes clear that a global energy transformation is urgently required, and that renewable energy, energy efficiency and electrification are the main cornerstones of that transition. Technologies for these pillars are available today, are deployable at a large scale quickly and are cost-competitive. The Paris Agreement was signed in 2015, and since then energy-related CO_2 emissions have risen by around 5%.

The coming years are critical: there is a need for a leap in collective ambition levels. Countries, and regions, must push for an energy transition that puts the world on a global pathway to reduced emissions, despite differing views on the mitigation measures needed. Key actions are needed now to promote the changes that are conducive to the energy transformation, including:

- ➜ **Transformation of the power sector to accommodate growing shares of variable renewable energy;**
- ➜ **Promotion of digitalisation as a key enabler to amplify the energy transformation;**
- ➜ **Acceleration of the electrification of the transport and heating sectors as a crucial component of the next stage of energy transformation;**
- ➜ **Adoption of hydrogen produced from renewable electricity to help reduce fossil fuel reliance in challenging sectors to reduce emissions;**
- ➜ **Development of biomass supply chains that are key to meeting growing demand for sustainable bioenergy.**

Decarbonising the global energy system requires swift and decisive policy action in the power, industry, buildings and transport sectors. An overview of major actions at the sector level is presented in Figure 3.12.

Figure 3.12. Global energy decarbonisation: Swift action needed in all sectors
Key actions at a sectoral level to realise the energy transformation to 2050

Power

ACCELERATE RENEWABLE CAPACITY ADDITIONS TO GENERATE ADEQUATE POWER WITH LOW-CARBON TECHNOLOGIES

1) Identify and map renewable energy resources and develop a portfolio of financeable projects for the medium to long term.
2) Construct no new coal power plants and plan and implement an end-of-life phase-out of coal capacities.

UPDATE GRID PLANNING TO ACCOMMODATE RISING SHARES OF VARIABLE RENEWABLE ENERGY (SOLAR AND WIND)

1) Develop a flexible power system (with flexible supply, storage, demand response, power-to-X, electric vehicles, digital and ICT technologies, etc).
2) Update grid codes.
3) Deploy micro-grids to improve resilience and expand energy access with renewable sources.
4) Deploy super-grids to interconnect regions.
5) Deploy cost-reflective tariff structures by properly readjusting the balance between volumetric charges (USD/kWh), fixed charges (*e.g.* USD/meter-month) and, where applicable, demand charges (USD/kW).

SUPPORT DISTRIBUTED ENERGY RESOURCE DEPLOYMENT

1) Incentivise energy consumers to become prosumers.
2) Support regulatory and pricing policies, including rights to generate and sell electricity, tariff regulation and grid-arrival policies.
3) Enable energy aggregators to foster use of distributed energy resources.

Transport

REDUCE TRANSPORT VOLUME AND CONGESTION

1) Adopt advanced digital communication technologies to improve urban transport planning and services (*e.g.* re-routing to reduce traffic congestion).
2) Promote mobility services (*e.g.* automonous driving, vehicle-sharing).
3) Accelerate the shift from passenger cars to public transport (electric railways, trams or buses).
4) Deploy low-emissions city trucks.

ACCELERATE THE SHIFT TO ELECTRIC MOBILITY

1) Set minimum standards for vehicle emissions.
2) Give electric vehicles (EVs) priority in city access.
3) Incentivise the development of charging infrastructure.
4) Strengthen links between the power and transport sectors with integrated planning and policy designs (vehicle-to-grid services).

PRIORITISE BIOFUELS IN ROAD FREIGHT, AVIATION AND SHIPPING

1) Introduce specific mandates for advanced biofuels, accompanied by direct financial incentives and financial de-risking measures.
2) Adopt supporting policies to scale up sustainable production of first- and second-generation biofuels.
3) Eliminate fossil-fuel subsidies and implement carbon and energy taxes to increase the competitiveness of renewable-fuelled shipping and aviation.

Source: IRENA (2019a)

Industry

REDUCE ENERGY CONSUMPTION IN INDUSTRIES

1) Promote circular economy (material recycling, waste management, improvements in materials efficiency, and structural changes such as reuse and recycling).
2) Establish energy efficiency standards and ramp up actual efficiency levels.

ENABLE CORPORATE SOURCING OF RENEWABLES

1) Support a credible and transparent certification and tracking system for corporate renewable energy use.
2) Consider an energy market structure that allows for direct trade between companies of all sizes and renewable energy developers, *e.g.* through power purchase agreements (PPAs).
3) Work with utilities and other electricity suppliers to provide green corporate procurement options.
4) Empower companies to invest directly in self-generation.

ACCELERATE LOW-CARBON TECHNOLOGY DEPLOYMENT FOR INDUSTRIAL PROCESS HEATING

1) Remove existing barriers and Incentivise low-carbon heating methods (*e.g.* solar thermal heating, modern bioenergy and heat pumps).
2) Support emerging biomass and hydrogen technologies. Replace fossil fuel-based with renewable-based feedstocks and process heat (*e.g.* in iron and steel subsectors, ammonia production).

Buildings

REDUCE ENERGY CONSUMPTION IN BUILDINGS

1) Establish or enhance energy-efficient building codes and standards (including for appliances and equipment).
2) Adopt retrofitting and renovation programmes, including financing schemes.
3) Incentivise retrofits and adjust construction codes in cities and states.
4) Combine energy efficiency and renewable energy measures (*e.g.* public policies to integrate these technologies in renovations of public buildings).

SUPPORT AND FOSTER DER DEPLOYMENT

1) Remove barriers that prevent prosumers from actively helping to transform the energy system.
2) Promote community ownership models and innovative financing schemes.
3) Accelerate the roll-out of smart meters.
4) Capitalise on smart-home and digitalisation schemes to allow demand management and strengthen grid services.

SCALE UP THE RENEWABLE SHARE IN THE BUILDINGS SECTOR

1) Promote low-carbon heating technologies (*e.g.* heat pumps, solar heating, modern bioenergy for heating and cooling).
2) Apply these renewable energy technologies through district heating.
3) Phase out traditional biomass as a cooking fuel and replace it with clean and efficient cookstoves (biogas, modern solid biomass, electricity).

REGIONAL SOCIO-ECONOMIC IMPACTS

04

Socio-economic footprints provide essential insights for transition planning and policy making at the global level (Chapter 2), at the regional level (Chapter 4) and the country level (IRENA, 2020a and forthcoming country studies).

This chapter presents socio-economic footprints of the world's ten regions analysed in Chapter 3. The first section briefly describes the socio-economic context underlying the analysis. The second presents the results of the socio-economic footprint of the energy transition for each region. Some of the policy implications are presented in the concluding section, but also in Chapter 6, where the contours of a policy framework for a just energy transition are considered as part of a broader discussion of the transformative decarbonisation of societies.

4.1 Background

The socio-economic footprints of the world's regions differ significantly from aggregate global results and from each other. This is due to regional differences in 1) the prevailing socio-economic context and structures at the start of the energy transition; 2) the energy transition roadmap envisioned for each region under the Transforming Energy Scenario and the resources available; and 3) changes in economic structures and policy support for the energy transition.

The energy transition interacts in multiple ways with the socio-economic context in each region, producing its socio-economic footprint. It occurs in countries and regions that are at different stages of development, in different states of economic growth, with differing economic structures, and with populations possessing different capacities and needs. It is, therefore, essential to analyse the Transforming Energy Scenario and understand regional effects in detail.

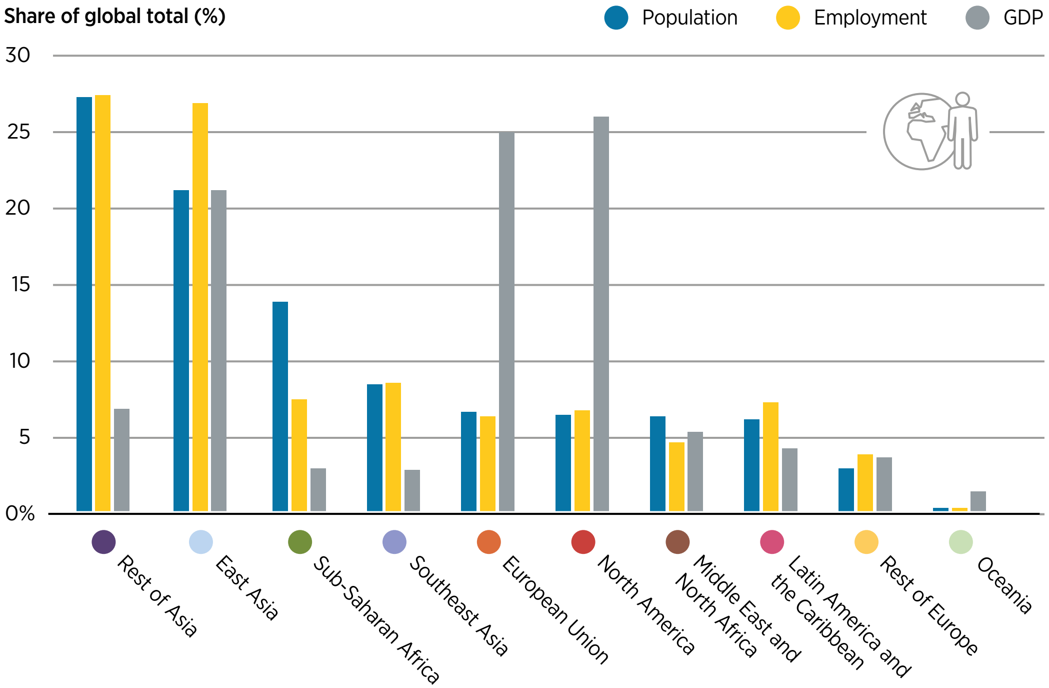
For this purpose, major socio-economic developments such as population growth are maintained at equal levels for any given time and region under the two scenarios.

GDP, employment and welfare effects are determined macro-econometrically, using the E3ME simulation model.[1]

The main socio-economic variables used to contextualise the analysis include the regional distribution of population, employment and GDP at the beginning of the transition, as well as the evolution of each variable over time. Figure 4.1 shows the regional distribution of population, economy-wide employment and GDP, ranked in decreasing order of population. More than half of global GDP arises from the European Union and North America. Sub-Saharan Africa, Southeast Asia, and Oceania each account for small shares of global GDP. Shares of jobs in global employment are highest in Asia, which also account for the highest share of population.

Figure 4.1 Some regions feature prominently in population and job distribution, others in GDP distribution

Regional shares of global population, economy-wide employment and GDP in 2019



IRENA analysis based on E3ME.

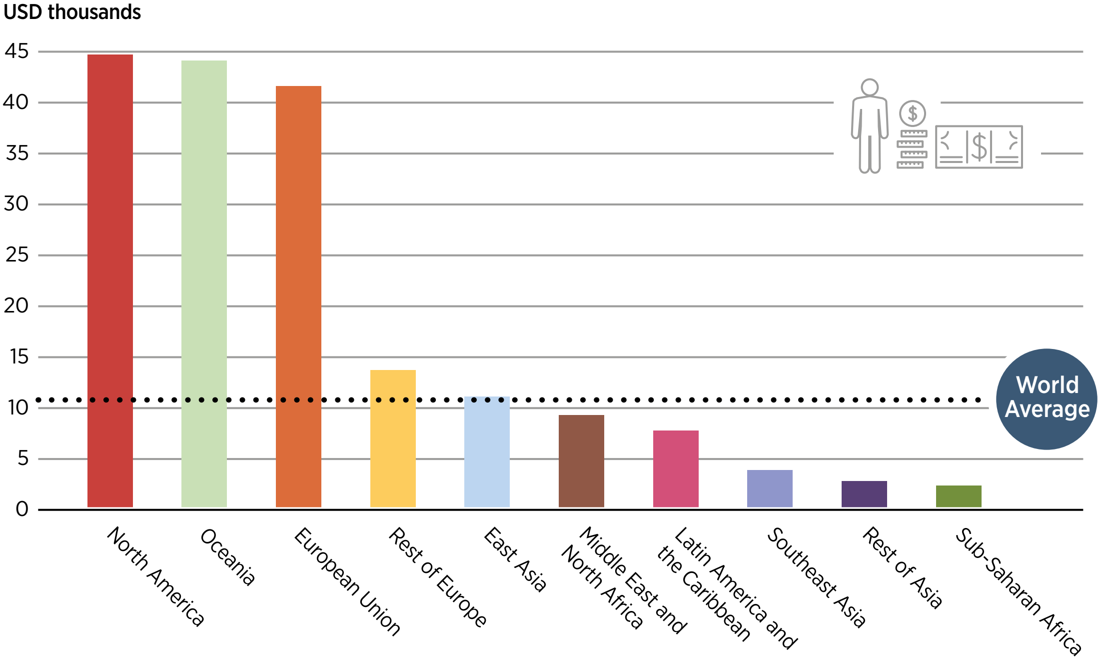
[1] E3ME is Cambridge Econometrics' macro-econometric model. IRENA's socio-economic footprint analysis uses the E3ME model to evaluate the systemic implications of transition roadmaps.

Absolute numbers can camouflage important differences on a per capita basis. Figure 4.2 compares regional per capita GDP figures. The dashed line indicates the global average of USD 11 000.[2] North America, Oceania (despite its small share of global GDP) and the European Union are well above it. The rest of Europe, East Asia and the Middle East and North Africa (MENA) have close to the average, while other regions fall below it. Figure 4.3 shows the evolution of the socio-economic context in each region and the world over the transition period (2019-2050), in terms of the compound annual growth rate (CAGR)[3] of population, economy-wide employment and GDP.[4]

The additional investment required to deploy clean energy technologies provides an essential input to regional development under the Transforming Energy Scenario.

Figure 4.2 North America, Oceania and the European Union: Per capita GDP well above the global average

Distribution of per capita GDP in 2019



IRENA analysis based on E3ME.

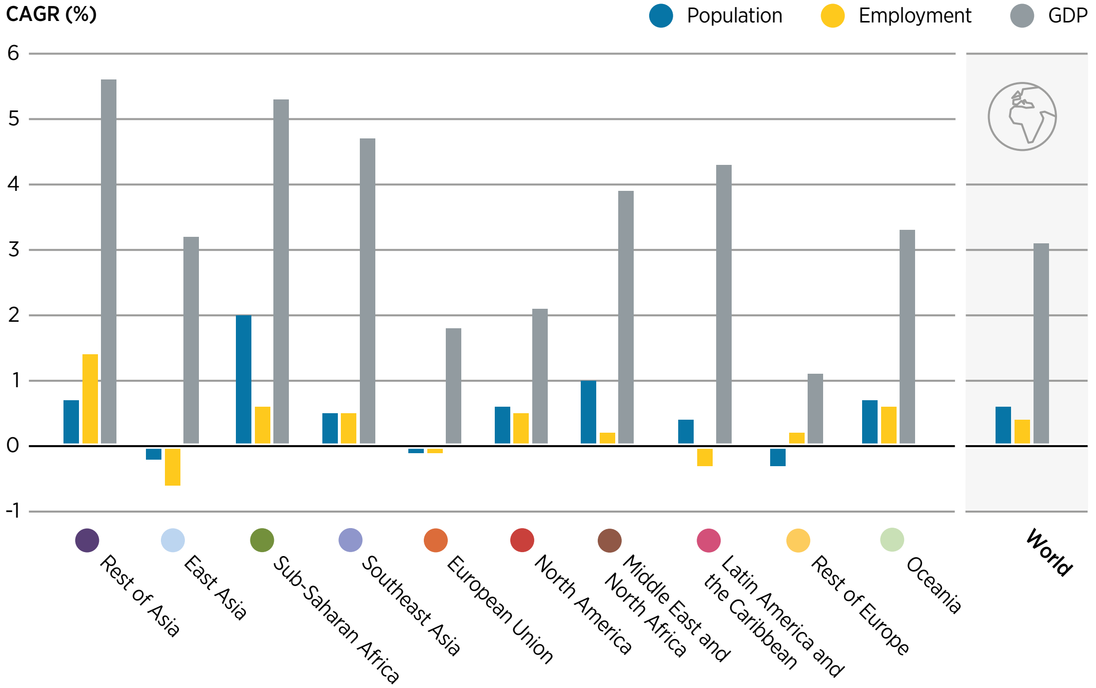
[2] All U.S. dollar values in this chapter are 2015 constant values.

[3] The compound annual growth rate is a measure of growth over a given period – in this instance 2017-2050. It can be thought of as the constant annual growth rate needed to move from the initial to the final value over that period.

[4] This is based on IPCC SS1 and SS2. The shared socio-economic pathways are part of a new scenario framework, established by the climate change research community to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation and mitigation. The SSP2 represents a middle-of-the-road socio-economic context, while the SSP1 is linked to a socio-economic narrative centered on sustainable development.

Figure 4.3 Growth rates of population, jobs and GDP vary across regions

CAGR of population, economy wide employment and GDP in ten regions worldwide under the Transforming Energy Scenario, 2019-2050



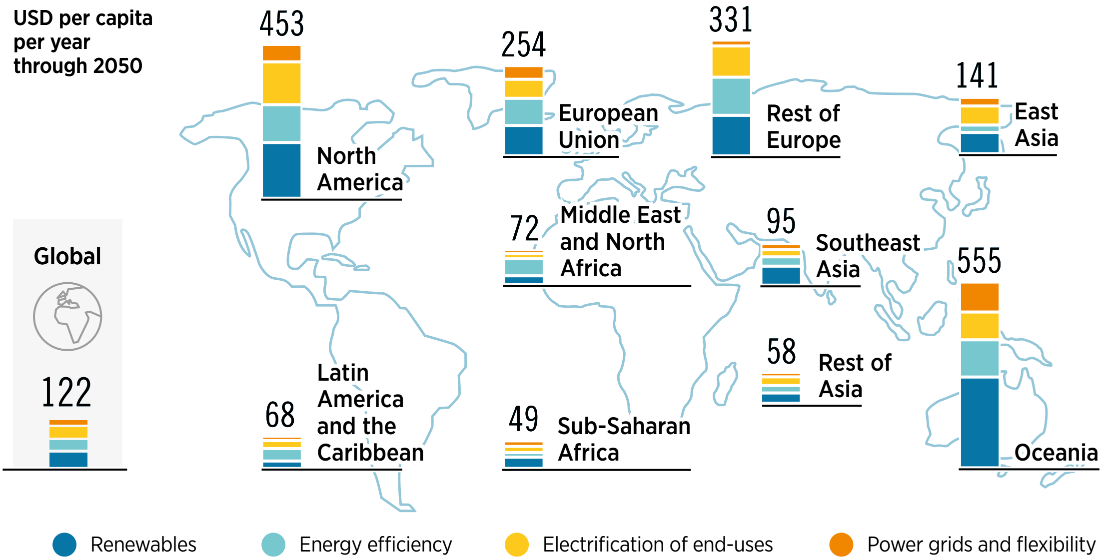
IRENA analysis based on E3ME.

Figure 4.4 presents the per capita distribution of the additional clean energy investment[5] needed for the transition mapped out in the scenario. With the global average standing at USD 122 per capita per year, investment differs across the regions, from around USD 50 per capita per year in sub-Saharan Africa to USD 455-555 in North America and Oceania.

The regional distributions of per capita GDP (Figure 4.2) and per capita additional clean energy investment (Figure 4.4) follow similar patterns. The path of investment over time will affect the regional socio-economic footprint, as will the region's readiness to absorb investment and benefit from it. These can have major impacts on distributional patterns of the regional socio-economic footprint (forthcoming IRENA).

[5] Additional investment is the investment in renewables, energy efficiency and energy flexibility needed for the Transforming Energy Scenario, minus that needed for the Planned Energy Scenario. The total additional investment is presented in Chapter 3 and in IRENA (2019a). In absolute terms, the cumulative total additional investment is USD 15 trillion, while the cumulative additional clean energy investment is USD 36 trillion. Globally, total additional average per capita investment during the transition is USD 54 per capita per year (using the average 2019-2050 population). Total additional investment is lower mainly because of the reduction in fossil-fuel investment occurring in parallel with clean energy investment.

Figure 4.4 Clean energy investment per capita varies widely among regions
Annual per capita additional clean energy investments for the Transforming Energy Scenario, by region, through 2050



Based on IRENA analysis

Note: Per capita investment figures were calculated on basis of each region's average population during the period 2019-2050.

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4.2 Socio-economic indicators of the energy transition: Jobs

The energy transition affects different sectors and supply chains of the economy, induces technological changes and shifts investment – all with significant effects on employment, and hence on people's livelihoods. The most obvious changes will occur in the energy sector, with more jobs in renewables, energy efficiency and energy flexibility, and fewer jobs in fossil fuels. Here, the regional distribution of natural resources, both conventional and renewable, plays a role as important as that of manufacturing capacities and services.[6]

As the changes induced by the energy transition move through the economy as a whole, they bring about additional job gains and losses. These are described in this section for each region, beginning with employment in the overall energy sector and its constituent parts, then in the overall economy. Understanding these employment shifts will enable decision makers to pursue policies that ensure a just transition and leave no one behind.

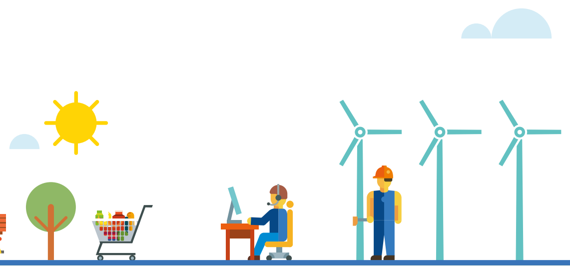
[6] Regional Factsheet presents further details on jobs in renewables and in the energy sector as a whole for each of the ten world regions considered in this report.

The following text distils findings from IRENA's econometric modelling work. Job numbers presented are for 2050 under the Transforming Energy Scenario, unless otherwise specified. Gains or losses describe, in absolute or relative terms, the difference between the Planned Energy Scenario and the Transforming Energy Scenario.

JOBS IN THE OVERALL ENERGY SECTOR

Employment in the energy sector is made up of jobs in the three transition-related technologies (renewable energy, energy efficiency, and power grids and energy flexibility) plus jobs in the conventional sectors (fossil fuel and nuclear industry) (IRENA, 2020a).[7] The regional and technological distribution of the 100 million energy sector jobs in 2050 under the Transforming Energy Scenario is illustrated in Figure 4.5. Asia is dominant with a 60% share (and East Asia alone accounts for about 35%). Compared with the Planned Energy Scenario, all regions gain jobs under the Transforming Energy Scenario. But Southeast Asia experiences the largest differential (81%), followed by Oceania (57%), Sub-Saharan Africa (36%) and North America (28%).

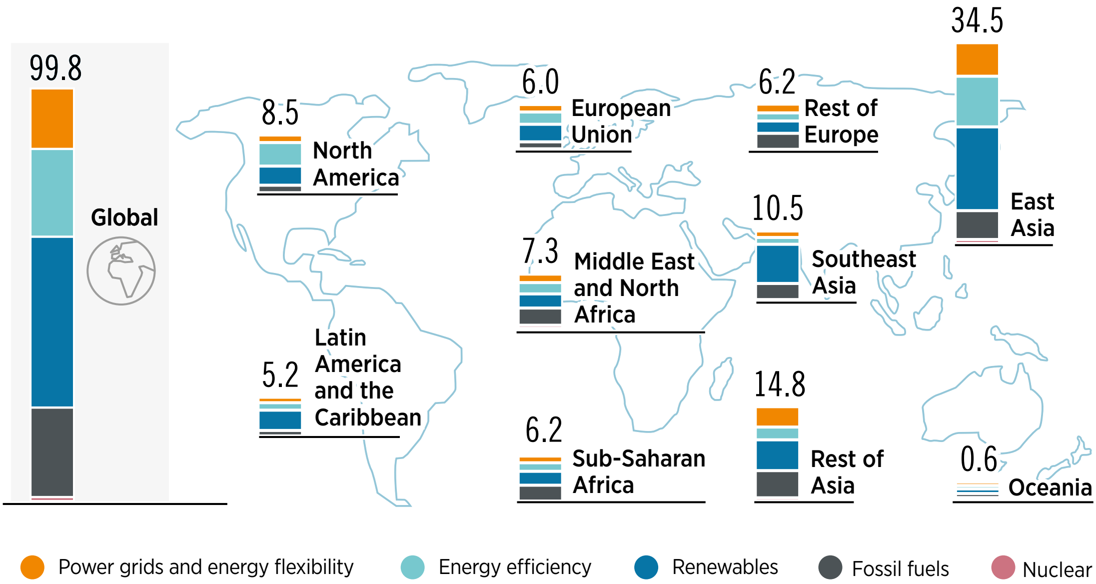
As shown in Chapter 2, the rise in total energy jobs between the two scenarios in 2050 (from around 87 to 100 million) results from gains in transition-related technologies and smaller losses in fossil fuel and nuclear sector jobs. Figure 4.6 shows the net employment effects in the energy sector for different regions. Interregional variations are explained by differences in the current structure of the energy sector, different energy sector roadmaps and the regional trade balances associated with transition-related equipment.



All regions create more energy sector jobs, even those where fossil fuel job loss is significant.

[7] Globally, jobs in renewables increase from 26 to 42 million; energy efficiency from 18 to 21 million; and energy flexibility from 13 to 15 million. Jobs in fossil fuels decrease from 30 to 22 million; nuclear from 0.7 to 0.4 million.

Figure 4.5 A hundred million energy jobs: Regional distribution
Energy sector jobs in 2050 under the Transforming Energy Scenario, by region (in millions)



Regional jobs as a percentage of total global jobs

North America	Latin America and the Caribbean	European Union	Middle East and North Africa	Sub-Saharan Africa	Rest of Europe	Southeast Asia	Rest of Asia	East Asia	Oceania
8.5%	5.2%	6.0%	7.3%	6.2%	6.2%	10.5%	14.8%	34.6%	0.6%

Based on IRENA analysis

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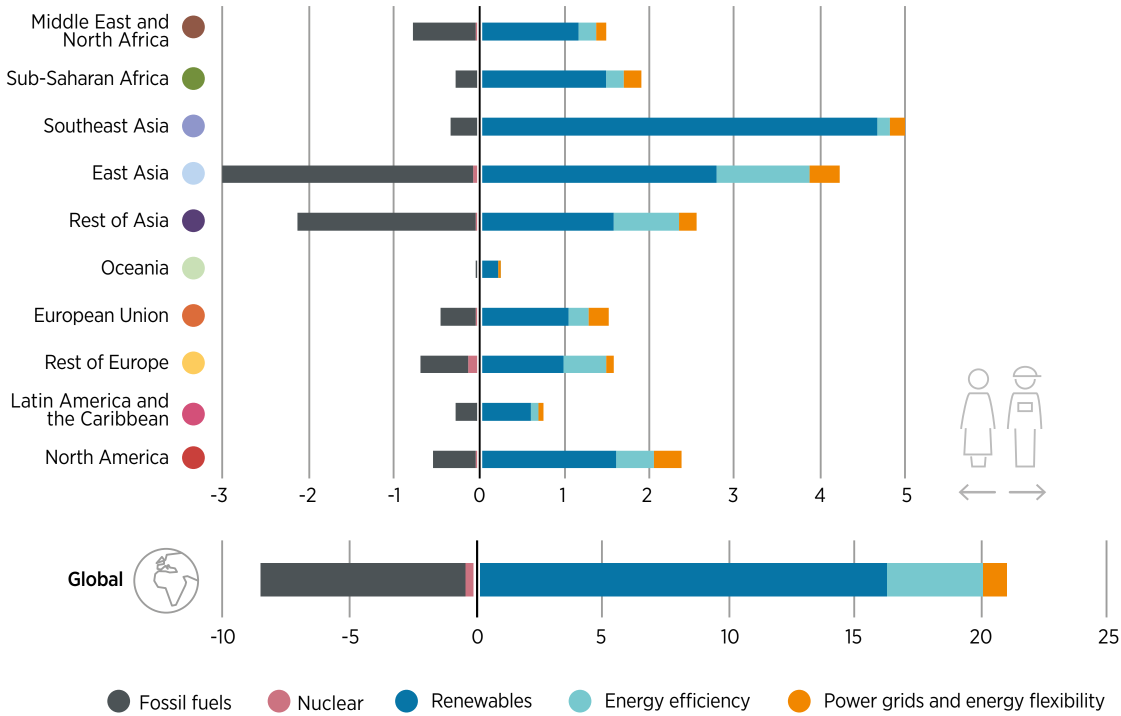
Figure 4.6 All regions gain more energy sector jobs than they lose

Difference in employment by 2050 between the Transforming Energy and Planned Energy scenarios, by region and sector (in millions)



Based on IRENA analysis

Transition-related jobs

Under the Transforming Energy Scenario, transition-related technologies (consisting of renewable energy, energy efficiency, and energy flexibility and grid enhancement) experience growth in employment across the world. In all regions, these technologies will employ more people in 2050 than conventional technologies will – accounting for as much as about 85% of all energy jobs in North America, the European Union, Latin America and the Caribbean and East Asia to about 60% in Sub-Saharan Africa and the rest of Europe.

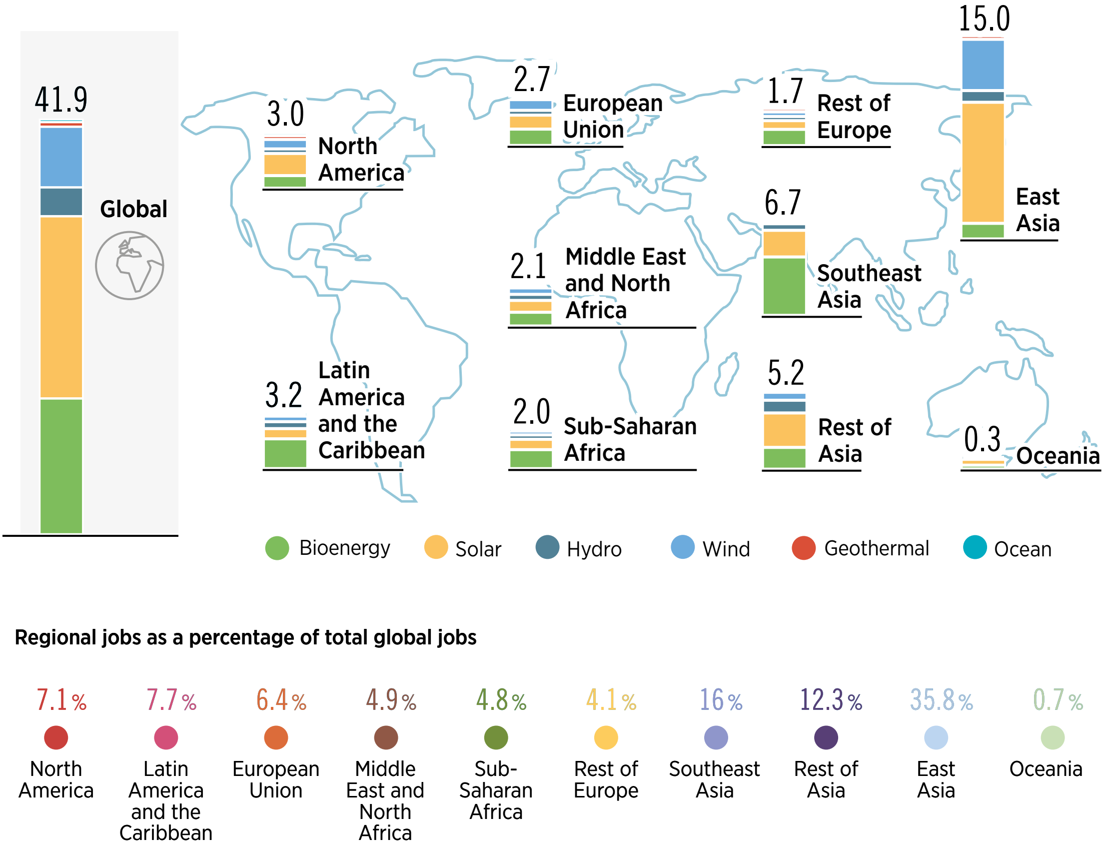
Among the transition-related technologies, renewable energy jobs feature most prominently in Southeast Asia and Latin America and the Caribbean (with shares of 64% and 62%, respectively, of all transition-related employment), about double the share in the MENA region and the rest of Europe. By contrast, energy efficiency jobs weigh in most heavily in North America (45%), while energy flexibility and grid enhancement jobs have the highest share (22%) in rest of Asia.

Additional findings for these categories of transition-related technologies, with particular focus on renewable energy, follow below.

Renewable energy jobs

About 42 million people will work in manufacturing, installing, operating and maintaining renewable energy systems in 2050 under the Transforming Energy Scenario, most in solar energy, followed by bioenergy and wind energy (see Figure 4.7). The greatest number of these jobs will be created in Asia: East Asia (36%), Southeast Asia (16%) and the rest of Asia (12%). The Americas rank second (15%), evenly split between North America and Latin America and the Caribbean. Europe holds a 10% share (with the European Union accounting for 6% and the rest of Europe for 4%). The shares for Sub-Saharan Africa and the MENA region are 5% each.

Figure 4.7 An estimated 42 million jobs in renewables: Regional distribution
Renewable energy jobs in 2050 under the Transforming Energy Scenario, by region (in millions)



Based on IRENA analysis

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In terms of technology share in each region, solar will account for half of all renewables jobs in North America and Asia, followed by Europe with 30%. By contrast, bioenergy is most prominent, with a share of over 60% of renewables jobs, in Latin America and the Caribbean, Southeast Asia, Sub-Saharan Africa and the rest of Europe. Wind is strongest in East Asia and the European Union with around 25% of jobs, and around 15% in North America and the MENA region. Hydro jobs account for 15% of all renewable energy jobs in rest of Asia and 10% in Latin America and the Caribbean and the MENA region.

In East Asia, renewable energy employment consists chiefly of jobs in solar energy and wind energy. To a large extent, investment in installations accounts for this result, driven by ambitious targets for the electricity sector. Many employment opportunities arise in manufacturing, trade and services. In addition, the region's exports of solar and wind technologies remain high, although manufacturing of the former is largely automated and, thus, of decreasing relevance to employment.

Southeast Asia starts from different initial conditions and will take a different route in the energy transition. Some solar manufacturers have recently moved to the region. But future developments will also be driven by bioenergy, which requires primarily domestic inputs and creates jobs in the labour-intensive agricultural sectors of the region.

The rest of Asia follows a mixed pattern between these two approaches, without the strong contribution of wind energy observed in East Asia. In Latin America and the Caribbean, a mature bioenergy sector makes a substantial contribution to regional employment, because the biomass and the technology needed to process it are largely domestic operations, as is the distribution of biofuels.

North America and Europe hold similar shares of global renewable energy employment, albeit with different specialisations. While North America generates jobs in the solar industry (manufacturing, sales and installation), Europe has a larger role for wind energy.

Energy efficiency

The share of energy efficiency jobs among all energy sector jobs in 2050 is projected to be highest in North America (45%). In the European Union, it will be 29%. It is expected to be lowest in Southeast Asia (7%), while other regions fall between 10% and 25%.

Individual regions also fare differently when it comes to the job growth differential between the Planned Energy Scenario and the Transforming Energy Scenario. Thanks to higher investments, the rest of Europe is estimated to more than double employment in energy efficiency. The rest of Asia also experiences a significant increase (75%), while gains in other regions vary between 10% and 30%.

Power grids and energy flexibility

With respect to power grids and energy flexibility, the share of jobs is highest in the rest of Asia (22%) and the rest of Europe (17%) and lowest in Southeast Asia (6%). Compared to the Planned Energy Scenario, the gains will range from over 65% in North America to more modest increases of about 6% in the rest of Europe, East Asia and the rest of Asia.

Conventional energy

In contrast to the transition-related technologies, projected 2050 employment in the conventional energy sector is lower in all regions in the Transformation Energy Scenario compared to the Planned Energy Scenario. The largest drop, around 40%, is likely to occur in North America, East Asia and the European Union. The rest of Asia follows with a decline of more than 30%, while Latin America and the Caribbean and the MENA region face a reduction of about 25% jobs.

Most of these losses will take place in the fossil fuel industries. They concern not only exporters but also importers who have built up extensive infrastructures, distribution networks, assets and human know-how around these forms of energy. Such developments notwithstanding, the share of conventional energy jobs does remain high in some regions. They will still account for up to 40% in Sub-Saharan Africa, the MENA region and the rest of Europe compared with just 10% to 15% in the European Union, the Americas and East Asia.

Coal mining is a labour-intensive sector that will lose many jobs in regions such as East Asia, the rest of Europe, and countries in Sub-Saharan Africa, such as South Africa. Other fossil fuel rich regions, notably the MENA region and North America, will also lose jobs in oil and gas.

In the **nuclear energy** sector, all regions are expected to lose jobs, ranging from 20% in Latin America and the Caribbean and the rest of Asia to around 65% in Europe and North America. This is mainly due to the age of the nuclear power plants. Notably, nuclear energy jobs often require highly educated experts, who would likely need different kinds of compensatory measures than fossil fuel sectors. However, the work force in the nuclear industry is older on average than in other energy sectors, so job losses can be more readily absorbed by pension schemes.

For the design of transition policies, the structure of qualifications in the lost jobs will be as relevant as the age structure of the labour force and the sub-regional distribution. Detailed analysis will be needed to design optimal policies.

Energy is an integral part of the economy, interacting with every other economic sector, affecting relative wages and generating income to be spent in other sectors.

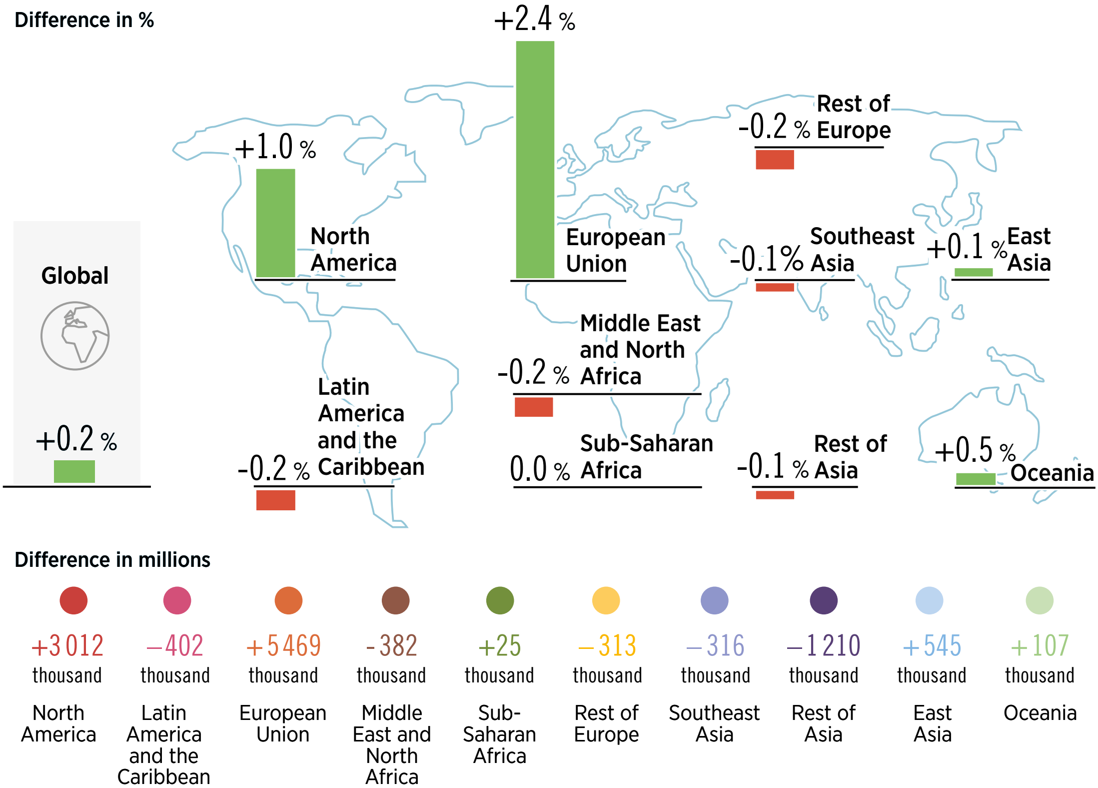
ECONOMY-WIDE JOBS

Energy is an integral part of the economy, interacting with every other economic sector, affecting relative wages and generating income to be spent in other sectors. Thus, labour impacts of the transition reach beyond the energy sector.

Figure 4.8 presents the economy-wide difference in regional employment between the Transforming Energy Scenario and the Planned Energy Scenario. Some regions enjoy gains significantly higher than the global average, while others experience a reduction.

The European Union shows the largest and most positive effect, with a 2.4% gain, followed by North America (1%) in 2050. Oceania and East Asia also benefit, but more marginally. With the exception of Sub-Saharan Africa, which shows no overall change,

Figure 4.8 The European Union stands to gain the most jobs economy-wide
Difference in regional employment in 2050 between the Planned Energy Scenario and the Transforming Energy Scenario (% and millions)



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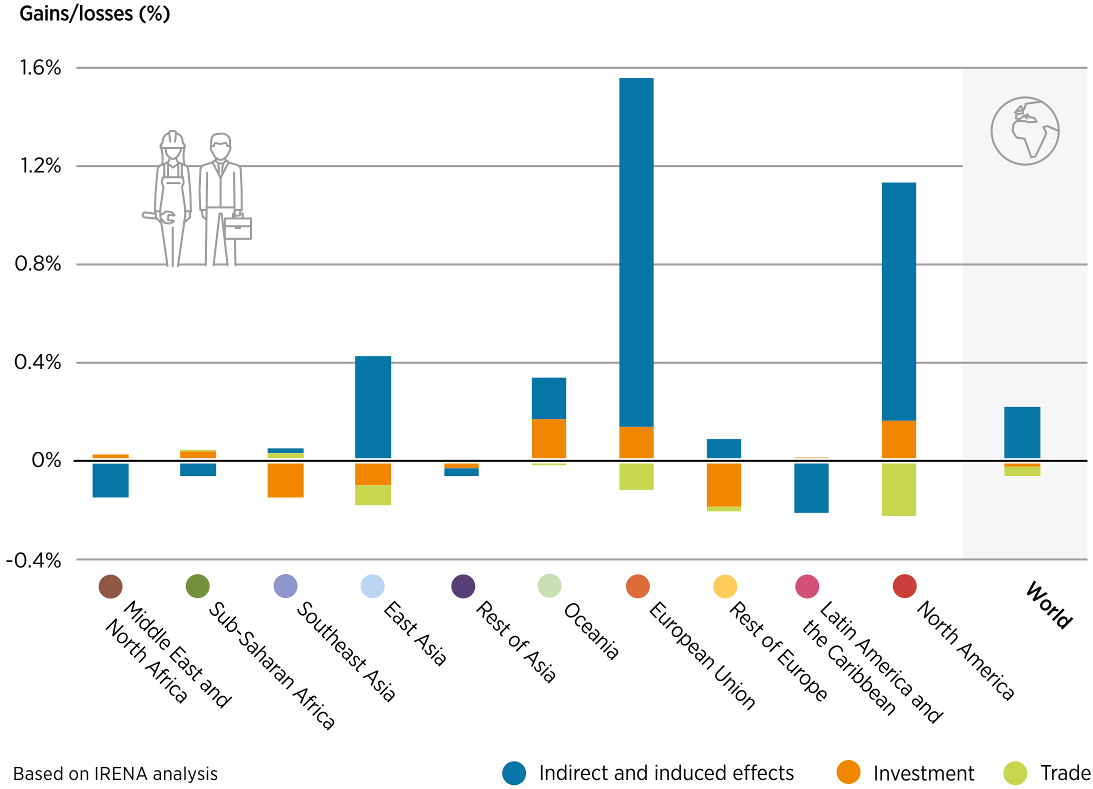
all other regions experience a decline of jobs. However, it is important to note that this loss is not absolute, but rather relative compared to likely outcomes under the Planned Energy Scenario.

As noted previously, whether a region experiences a gain or reduction in economy-wide jobs during the transition depends on both the inputs from the energy transition roadmap and the region's initial socio-economic and structural development. Countries that are well integrated in international trade and have a diversified economy are likely to gain from an investment-oriented strategy. Such regions are best able to absorb investment and expand their activities in machinery, electronics, services and the public sector. The workforce is qualified and administrative barriers are low. This holds true for North America, Europe and Oceania, and increasingly for East Asia.

Figure 4.9 Indirect and induced effects: Strongest in the European Union and North America
Role of three sets of drivers in the differences in regional economy-wide employment between the Transforming Energy Scenario and the Planned Energy Scenario for the 2019-2050 period



Based on IRENA analysis

To gain insights into what drives the net effects described so far, the jobs footprint is evaluated dynamically across the transition period, with the effect of each driver quantified for each region. Figure 4.9 shows the average role that each set of drivers plays during the transition on economy-wide employment between the Planned Energy Scenario and the Transforming Energy Scenario. The various drivers affect each region in strikingly different ways.

Change in employment numbers is of course only one dimension. Equally if not more critical is the issue of altered occupational and skills patterns as the energy transition takes hold. This will have profound impacts on labour markets and on educational and training institutions as skills demand and supply may show significant, even if temporary, mismatches.

In all regions, the transition-related job gains will surpass losses in conventional energy (see Regional Factsheets). However, the transition can still produce labour market misalignments in regions and countries that must be considered in defining related policies. The challenge is greater in those regions and countries where economy-wide results indicate less job growth under the Transforming Energy Scenario than under a business-as-usual approach (shown in Figure 4.8).

The misalignments can be grouped into four categories, namely temporal, spatial, educational and sectoral. Job gains and losses may not happen within the same time scale. New jobs may not be created in the same locations where jobs are lost. The specific educational and skill requirements may diverge. And finally, given that clean energy solutions will draw on a different set of supply chain inputs than the conventional energy industry, some economic sectors will gain while others lose. Avoiding or minimising these types of misalignments will be a major task of transition policy-making.

Change in employment numbers is only one critical dimension; altered occupational and skills patterns is another.

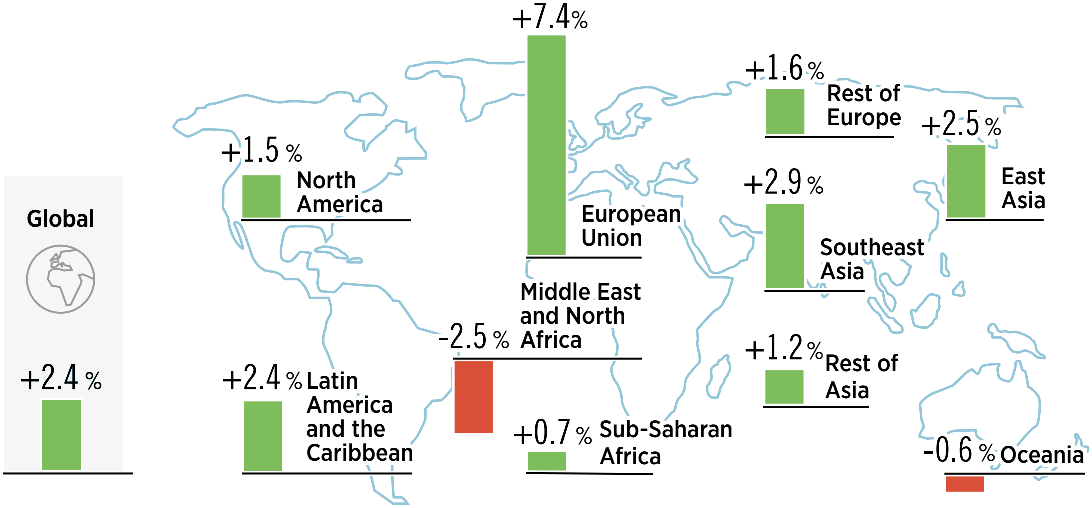
4.3. Socio-economic indicators of the energy transition: GDP

GDP has been the indicator most commonly used to guide economic policy and remains a proxy of well-being. The potential impact of the transition on GDP, therefore, is vital to understand, while simultaneously restructuring economies in line with the goal of improving welfare (see section 4.2.4). The Transforming Energy Scenario leads to a global increase in GDP compared with the Planned Energy Scenario, as demonstrated in Chapter 2; the regional impacts are presented in Figures 4.10 and 4.11. Regional GDP is driven by regional investment, the region's trade with the world, and induced and indirect effects in the region (see Chapter 2 and IRENA, 2019a).

Figure 4.10 presents the regional distribution of the differences in GDP between the Transforming Energy Scenario and the Planned Energy Scenario in 2050. Six regions (the MENA region, Oceania, Sub-Saharan Africa, the rest of Asia, North America, and the rest of Europe) have lower gains than the world average; two of them (the MENA region and Oceania) experience a reduction in GDP in 2050 compared with the Planned Energy Scenario. Three regions (Southeast Asia, East Asia and Latin America and the Caribbean) show GDP differences close to the world average in 2050. Only the European Union registers a GDP difference under the Transforming Energy Scenario that is higher than the world average.

Figure 4.10 All regions except two see GDP rise

Percentage difference in regional GDP between the Planned Energy Scenario and the Transforming Energy Scenario, 2050



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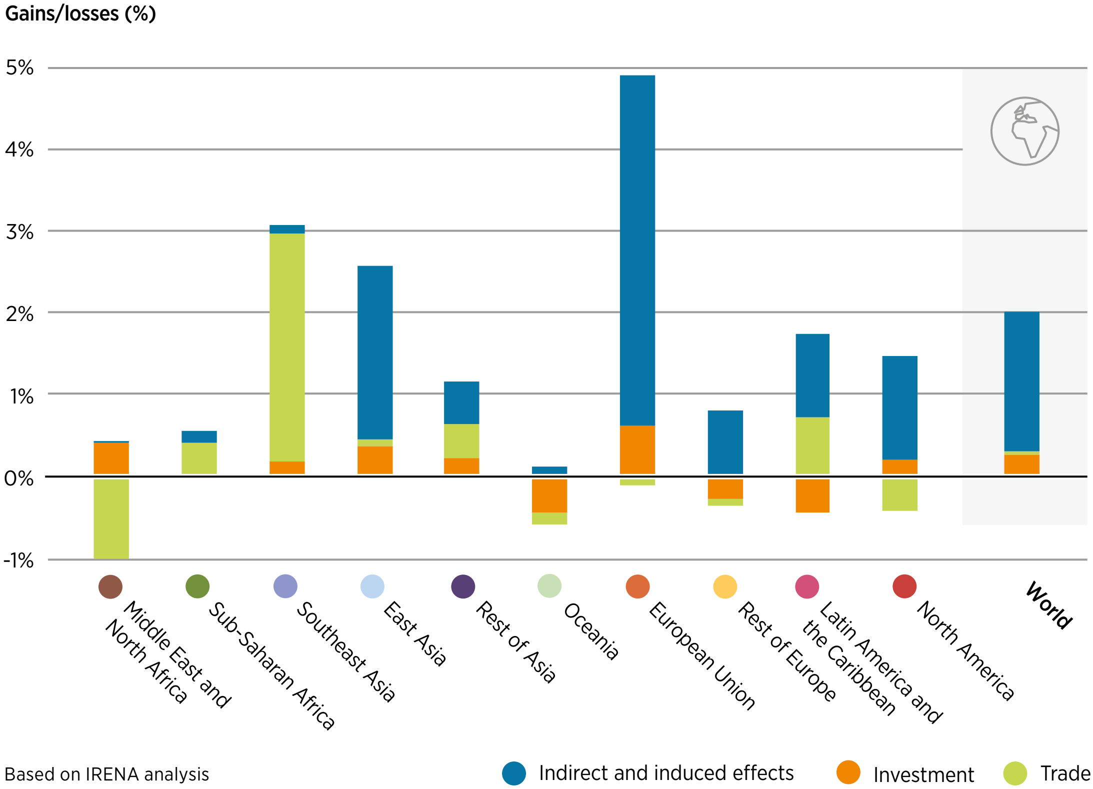
The reasons for these very different regional GDP results reside in the regional distribution of the inputs associated with the energy transition roadmap, differing regional macroeconomic structures and the linkages between regions.

IRENA's analysis demonstrates the impact on regional GDP of the three main drivers described in Chapter 2. Figure 4.11 shows how much GDP changes during 2019-2050 between the Planned Energy and Transforming Energy scenarios.

Figure 4.11 The largest drivers of GDP gains: Indirect and induced effects, and trade
Role of three sets of drivers in the differences in regional GDP between the Transforming Energy Scenario and the Planned Energy Scenario for the 2019-2050 period



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Trade: Trade plays a prominent role in shaping the future of some regional economies. The large GDP gains in Southeast Asia and Sub-Saharan Africa are attributable to a strong increase in net exports while the MENA region faces the opposite dynamic, driven by the loss of hydrocarbon exports. The positive trade effect in Latin America and the Caribbean and rest of Asia is quite pronounced while North America faces a drag from reductions in fossil fuel trade and even more so trade in other goods and services.

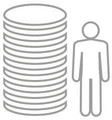
Investment: The level of investment is another important driver of the socio-economic outcome at regional levels. At the global level, transition-related energy investments average USD 122 per capita per year. Among regions the amounts vary widely, from around USD 50 per capita per year in Sub-Saharan Africa to USD 555 per capita per year in Oceania. Not only are the macroeconomic impacts consequently higher where investments are larger, but the multipliers in each economy play a significant role in determining the strength of investment effects.

Indirect and induced effects: The presence of robust supply chains allows indirect and induced effects to contribute positively to the economy, especially if supported by appropriate fiscal policies. This is particularly the case in some of the major economic regions, such as the European Union, East Asia and North America. Additional employment leads to additional income, which has multiplier effects by increasing consumer spending and economic activity. Fiscal policies are most effective if they are based on a clear understanding of the local socio-economic context in a given region or country. Furthermore, their successful implementation hinges on the presence of a complex administrative infrastructure.

If the energy transition brings employment gains in a given region, induced effects contribute positively to its economy. Additional employment leads to additional income, which has multiplier effects through additional consumer spending. This is the case in Europe, East Asia and North America. These results highlight the fact that when structural conditions of an economy (and its underlying supply chains) are well-positioned to embrace the challenges and opportunities of the energy transition, considerable gains can be expected not only in employment, but also in GDP.

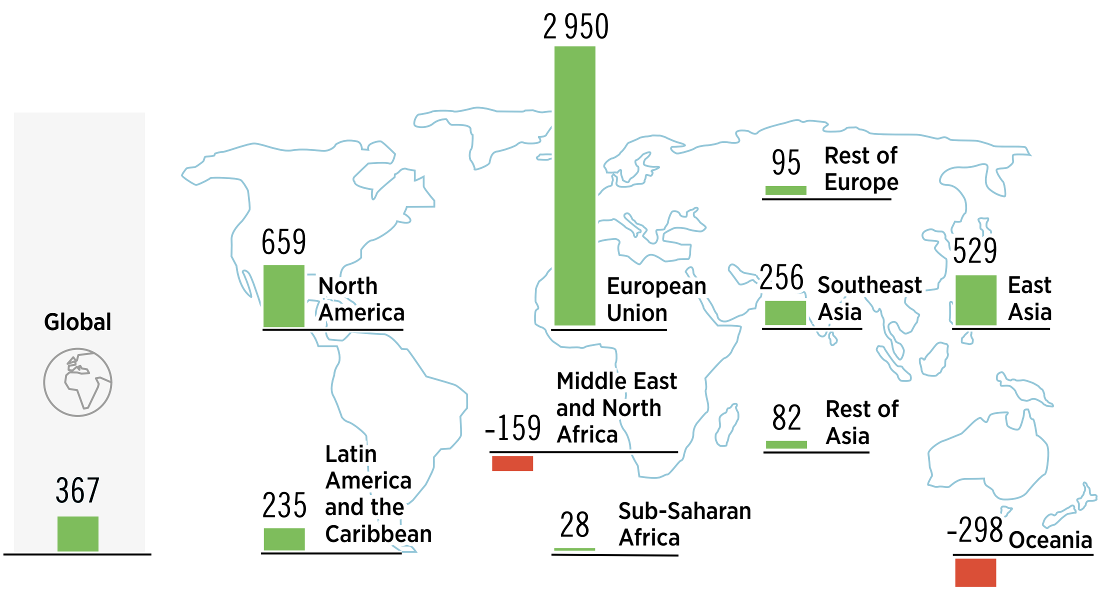
When structural conditions of an economy are well-positioned to embrace the challenges and opportunities of the energy transition, considerable gains can be expected in GDP and employment.

Whereas Figure 4.10 presents the regional distribution of GDP in the year 2050, Figure 4.12 shows the cumulative results between 2019 and 2050, *i.e.*, the sum of GDP differences between the Planned Energy Scenario and the Transforming Energy Scenario. For the world, this cumulative difference in GDP is USD 98 trillion (see Chapter 2), which in per capita annual terms (using the average population in the years between 2019 and 2050) represents USD 367 per capita per year.



The European Union is expected to gain as much as USD 2 950 per capita per year, but for most regions it is between USD 660 to about USD 100. Sub-Saharan Africa is projected to experience a modest increase of around USD 30, while the MENA region and Oceania see a decline relative to the Planned Energy Scenario. Variations in economic footprint contribute to the differences in the welfare estimates for these regions (Figure 4.12).

Figure 4.12 Regional differences in GDP gains per capita
Regional cumulative GDP gain under the Transforming Energy Scenario compared with the Planned Energy Scenario (in USD, per person per year)



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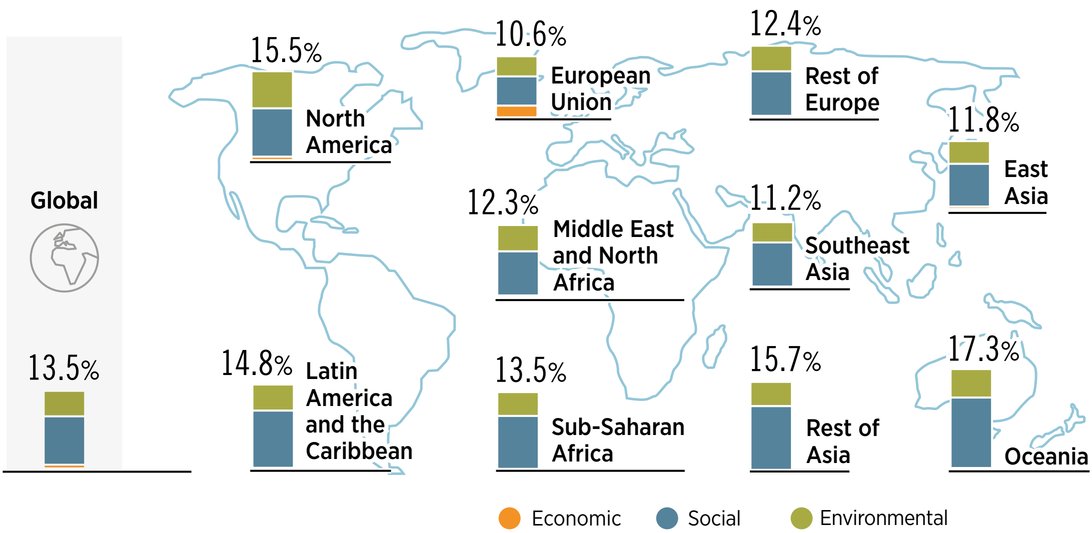
WELFARE

Although employment and GDP are relevant indicators for the public debate, the improvement of people's well-being must be the ultimate target of any change or transition. Welfare, therefore, is one of the most important socio-economic indicators of the energy transition. The strong positive impact of the transition on global welfare is presented in Chapter 2 (a positive difference of 13.5%).[8]

Figure 4.13 shows its regional distribution in 2050. The Transforming Energy Scenario leads to a much more significant improvement in welfare than the Planned Energy Scenario. Some regions fare better than others, with Oceania seeing an improvement in welfare above 17%, while Europe improves by 10% and the other regions fall between these levels.

Figure 4.13 Welfare improvements at regional levels driven by social and environmental gains
Gain in welfare indicator in 2050 between the Transforming Energy and Planned Energy scenarios (in %)



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[8] For further details on the structure of the welfare indicator for each of the 10 regions, as well as its evolution over time (2030 and 2050), see Regional Factsheets.

Among the different welfare dimensions (as described in Chapter 2), the social and environmental ones dominate the gains in every region. Within the social dimension, the reduction in illness and disease caused by local air pollution accounts for the most improvement. Hence, regions currently experiencing more outdoor and indoor air pollution achieve greater welfare improvements as the transition progresses. In some regions, such as Latin America and the Caribbean and East Asia, the other component of the social dimension (spending on education) also sees a very sizeable improvement as the transition advances.

Noteworthy is the share of the economic dimension in certain regions, including the European Union and North America, portraying the relatively higher economic and employment gains illustrated in the results above.

The dominant component within the environmental dimension, which is composed of sub-indicators on greenhouse gas emissions and consumption of materials, is the mitigation of global greenhouse gas emissions. The benefits from emission reductions are shared by all regions.

4.4 Policy conclusions

The foregoing analysis shows that all regions of the world can expect to derive benefits from the energy transition. However, settling for a broadly positive picture is simply not sufficient. As our modelling results indicate, individual regions will not gain equally much in the transition-related sectors; all will need to address impending losses in conventional energy, but some more so than others; and they must prepare for considerable differences in the extent to which their overall economies are able to benefit from the various drivers of the transition, *i.e.*, investments, trade, and indirect and induced effects.

The expected regional outcomes also vary depending on whether one examines impacts on GDP, employment or human welfare. Welfare gains are the area where gains are strong for all regions. The reason is that lower air pollution from the adoption of cleaner energy benefits people irrespective of economic prowess. Within the category of jobs, this chapter has focused on projected developments in the energy sector as a whole, plus its main constituent parts, transition-related and conventional energy, as well as the connections to the economy at large. Individual regions fare differently in each of these categories, sometimes strongly so.

The most important lesson, therefore, is the need for thorough analysis of the reasons for these regional differences. Ultimately, even more granular and detailed analysis is required in each country, as regional averages may conceal significant differences among countries. Understanding the socio-economic impacts is essential for countries exploring ways to maximise benefits, minimise adjustment burdens, and meet multiple objectives such as stimulating economic growth and employment, improving energy security, expanding energy access and mitigating climate change.

As mentioned in this chapter, differences in the regional socio-economic footprints can be traced back to differences in their structural conditions, industrial capacities, trade structures, and the depth and diversity of domestic supply chains. All help determine the degree to which a given economy can take advantage of the opportunities offered by the energy transition. It must be understood that some countries face greater challenges than others.

But while existing structures can help or hinder a country's ability to benefit from the transition, they are not written in stone. They can be altered over time, as know-how is accumulated, skills taught, supply chain capacities built, and institutional capacities enhanced. Policy ambition and far-sighted planning are critical. As such, transition planning needs to assess not only existing socio-economic structures, but also be aware of the profound changes the transition will bring about in labour markets. These can produce misalignments in many regions, which will unfold against the broader reality of structural unemployment that remains a critical issue for most countries.

To achieve a successful and just transition, investments in renewable energy, energy efficiency, and electrification of transport and other facets of the energy transition must be co-ordinated and integrated with other policies specific to the energy sector and broader policies to enhance the technical strengths and structural capacities of the economy. In other words, policies specific to the energy sector must be mainstreamed into economic, industrial, labour, education policies and social policies. The socio-economic indicators that a given policy aims to address should be clearly identified in order to overcome challenges and maximise benefits from the energy transition.

Cross-cutting and coherent policy-making can deliver on climate and energy ambitions, and put in place a mix of programmes, projects and initiatives to generate successful outcomes. In this context, it is essential to understand the structural conditions of specific economies and their related dependencies, including commodity, trade and technological (see Chapter 6).

IRENA's analysis underscores the urgency of policies for economic diversification as they leverage local capabilities along segments of value chains and address labour market rigidities. The specifics will vary from country to country, but a comprehensive package will need to include a broad mix of policies and interventions (see Chapter 6). In that, the energy sector - as a critical enabler of growth and development - is fundamental.

GETTING TO ZERO

05

Ensuring that global temperatures stop rising will require that, by the second half of this century, emissions eventually reach zero, or net zero. Additional mitigation measures will therefore be needed beyond what was presented earlier in the Transforming Energy Scenario. This chapter considers these increased mitigation needs and, with the Deeper Decarbonisation Perspective (DDP), presents enhancements to that scenario showing what more could be done.

5.1 Getting to zero: Technology options and costs

Carbon dioxide emissions represent three-quarters of greenhouse gas emissions[1], with energy-related CO_2 (combustion of fossil fuels) and industrial process emissions making up over 80% of CO_2 emissions and the remainder coming from land use, land-use change and forestry (LULUCF). Efforts are therefore needed across the energy, industrial and land-use sectors to reduce emissions. Significant efforts are needed in certain sectors, such as in industry and transport, that are sometimes referred to as “hard-to-decarbonise” or "hard-to-abate" sectors.

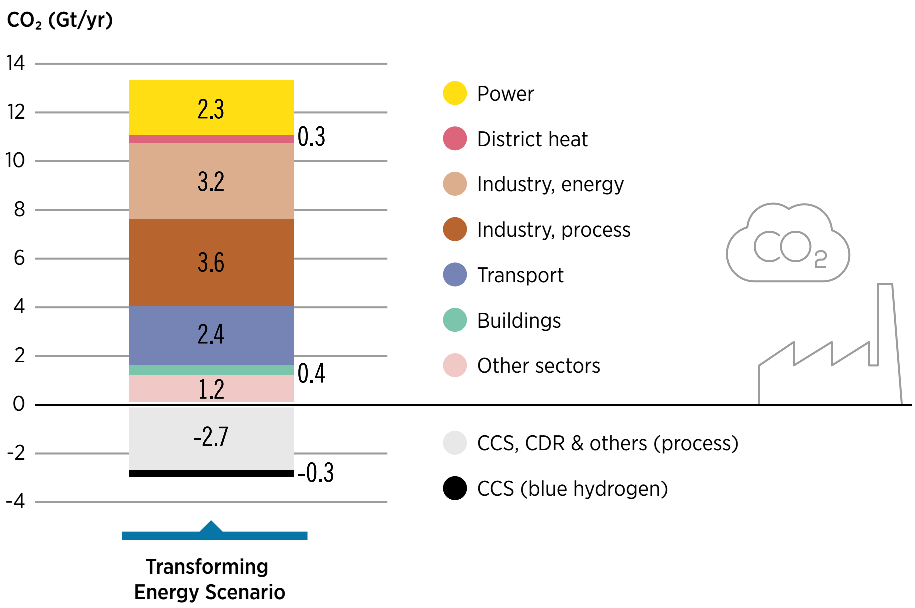
The analysis presented in this report separates CO_2 emissions into three categories: energy-related, industrial process and LULUCF[2]. The previous chapters of the report focus only on energy-related CO_2. This chapter expands the focus to include industrial processes due to the significance of these emission sources to the industry sector.

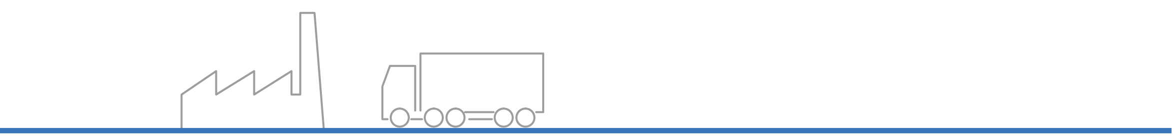
[1] Two-thirds of the remainder is methane, with most of the rest coming from nitrous oxide and fluorinated gases.

[2] LULUCF emissions are considered in the overall carbon budget, including assumptions for LULUCF that result in net-zero emissions for the period 2018-2100. However, detailing the measures that reduce LULUCF emissions are outside the scope of this report and are not analysed in detail, as this chapter is limited to energy-consuming sectors. The assumption is that CO_2 emissions from LULUCF would fall from 5.5 Gt in 2018 to zero by mid-century at the latest, and that LULUCF subsequently would become a net absorber of CO_2 over the remainder of the 21st century. As a result, cumulative CO_2 emissions from LULUCF between 2018 and 2100 would be zero.

In the Transforming Energy Scenario, 9.5 Gt of energy-related CO_2 emissions remains in 2050. Around 2.9 Gt of process emissions was emitted globally in 2016, which in the Planned Energy Scenario will increase to 3.6 Gt by 2050. In the Transforming Energy Scenario, this is reduced over 75% to 0.9 Gt. Carbon capture and storage (CCS) accounts for 2 Gt of the 2.7 Gt reduction, but reductions also are achieved through forms of carbon management, including offsetting through carbon dioxide removal (CDR) or reduced through material efficiency and the circular economy. Therefore, the Transforming Energy Scenario would result in 10.4 Gt of remaining net CO_2 emissions in 2050. Figure 5.1 outlines these remaining CO_2 emissions and their sources in 2050, with the bulk of these emissions found in the transport and industry sectors.

Figure 5.1 Industry and transport: The bulk of remaining emissions in 2050
Energy-related and industrial process CO_2 emissions in the Transforming Energy Scenario, 2050





There are two general approaches to reducing emissions to zero: completely decarbonising all energy and industrial processes so that no CO_2 is emitted at all (the "zero" emissions approach), and offsetting any remaining emissions through the use of CDR to achieve net-zero emissions (the "net-zero" emissions approach). Examples of CDR include reforestation, afforestation, direct air capture, enhanced weathering and bioenergy CCS.

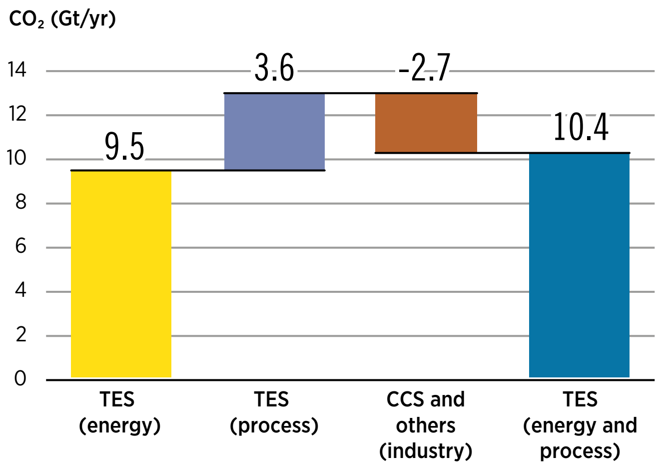
The optimal mix of these two approaches ("zero" and "net zero") needs to be further explored, in particular given the uncertainties about the types of technologies and solutions that could reduce these remaining emissions. The Deeper Decarbonisation Perspective described in this chapter do not constitute a new scenario; instead, they explain the two types of approaches that could further reduce the remaining emissions in the Transforming Energy Scenario in order to achieve zero, or net-zero, emissions.

The time scales on which these approaches could be implemented are also highly uncertain. Given that delivering the Transforming Energy Scenario by 2050 is already a significant challenge, the additional measures described in the Deeper Decarbonisation Perspective may require longer to fully implement. The following analysis assumes a policy objective to deliver the "net-zero" or "zero" approaches in the decade following 2050. It might be possible to shorten those time frames with sufficiently robust policy measurements, investment and improvements through innovation, but that is highly uncertain.

Figure 5.2 outlines, by technology category, the reductions that would occur by sector in the two approaches.

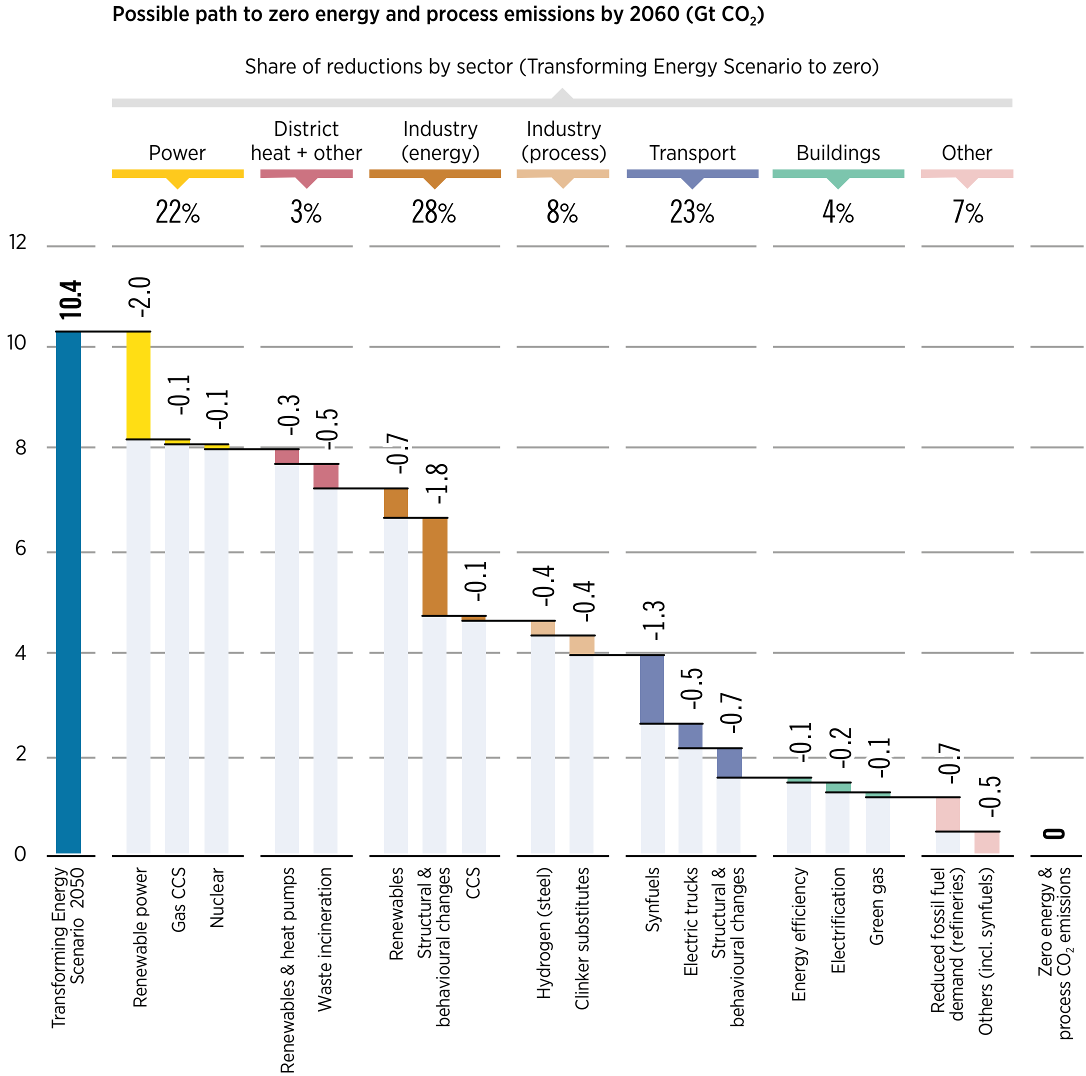
Figure 5.2 The Deeper Decarbonisation Perspective: Getting to "net zero" and eventually "zero" (figure continues on next page)

Remaining energy and process-related CO_2 emissions in the Transforming Energy Scenario



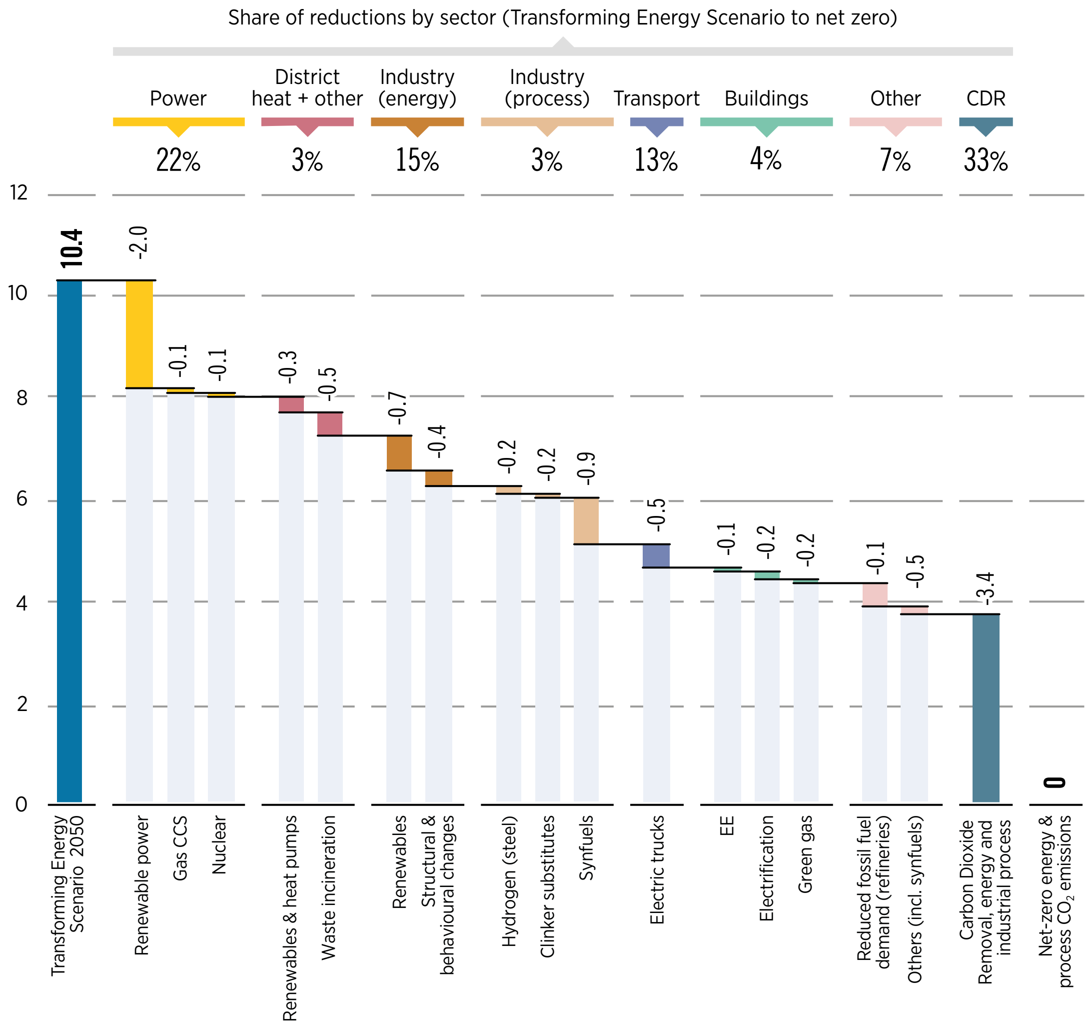
(figure continues on next page)

Figure 5.2 (continued)
Reductions in energy and industrial process CO_2 emissions in the Deeper Decarbonisation Perspective "zero" (left page) and "net zero" (right page) approaches



Note: The Transforming Energy Scenario includes 250 Mt/yr in 2050 of carbon capture, utilisation and storage for natural gas-based hydrogen production (blue hydrogen).

Deeper Decarbonisation Perspective to net zero energy and process emissions at the latest by 2060 (Gt CO_2)



Reducing the remaining emissions in the Transforming Energy Scenario requires numerous activities. For the power sector, emissions are reduced to zero through full deployment of zero-carbon electricity sources, mainly renewable energy coupled with storage or coupled with the use of hydrogen, although combining CCS with existing natural gas plants also plays a limited role. The buildings sector and the district heating sector are also fully decarbonised through increased electrification, which in turn is sourced from fully decarbonised electricity, or through the use of renewable end-use technologies, such as solar thermal or bioenergy, or through green hydrogen.

After these approaches, the remaining sectors with energy-related emissions are industry, transport and some other small sectors such as refining, forestry and fisheries. These sectors have 6.7 Gt of energy-related emissions remaining in the Transforming Energy Scenario.

The Deeper Decarbonisation Perspective "net-zero" approach reduces these remaining energy-related emissions to 3.4 Gt; therefore, it is assumed that an equal amount of carbon sinks is needed to offset these emissions to arrive at net zero, although the type of carbon sink is not defined. With robust policy measures and successful innovation it may be possible to reduce emissions from these sectors to zero without the need for carbon sinks. The Deeper Decarbonisation Perspective "zero" approach assumes further technology deployment, along with structural and behavioural changes, to arrive at fully zero emissions.

There is also 0.8 Gt of remaining industrial process emissions in the Transforming Energy Scenario that is not sequestered or offset. The Deeper Decarbonisation Perspective assumes that these remaining emissions are reduced through methods outlined in this chapter and that no further sequestering or offsetting of emissions for industrial process are needed.

A summary overview of the methods used to reduce both energy and process emissions under the Baseline Energy Scenario, the Transforming Energy Scenario and the two Deeper Decarbonisation Perspectives is presented in Figure 5.3. The reductions that result in shifting from the Baseline Energy Scenario to the Planned Energy Scenario reduce annual CO_2 emissions by 9.9 Gt. Almost half of the reductions are a result of renewable energy, with one-quarter coming from energy efficiency and the remainder coming largely from end-use electrification, primarily electric vehicles. This represents how government plans have changed over the last few years, reflecting the positive developments for renewable power and EVs.

In the Transforming Energy Scenario, annual CO_2 emissions are reduced in total by 26.3 Gt, with almost half coming from renewable energy, followed by a 24% reduction from energy efficiency, largely technical efficiency measures but also including structural changes such as the circular economy and other measures that reduce the consumption of energy-intensive and carbon-intensive products. Of the remaining emissions, 11% of reductions come from EVs, with the remainder split between green and blue hydrogen, CCS and others.

The Deeper Decarbonisation Perspective "zero" approach reduces the remaining 10.4 Gt of annual CO_2 emissions to zero. It shows a roughly equal importance of renewables, energy efficiency and other approaches for reducing the remaining emissions to zero, each contributing around one-third. Of the others, green hydrogen (which includes synthetic fuels and use as a feedstock) plays the most important role. For the Deeper Decarbonisation Perspective "net-zero" approach, renewables and energy efficiency still play an important role, but a large contributor to reductions is CDR, which reduces the reduction amount that is required across the other approaches.

Overall, when looking at the technology groupings that result in reducing annual energy and industrial process-related CO_2 emissions (a decline from the Baseline Energy Scenario value of 46.5 Gt to a value of zero in the Deeper Decarbonisation Perspective "zero" approach), renewables make up 43%, energy efficiency and structural changes 26%, EVs 12%, green hydrogen 9%, and the remainder a mix of blue hydrogen, CCS (9%), behavioural change and nuclear energy (Figure 5.3).

Figure 5.3 Renewables and efficiency: Achieving the bulk of emission reductions
Mitigation potential per technology grouping by scenario, 2020-2050 (PES, TES), 2020-2060 (DDP)

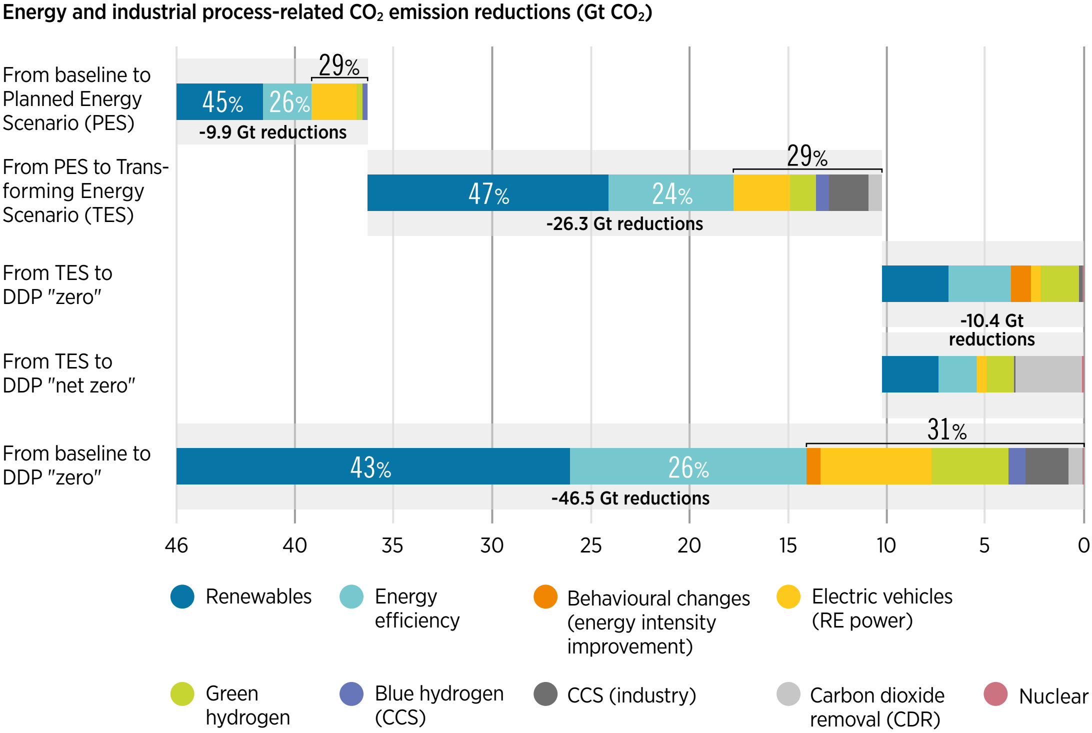


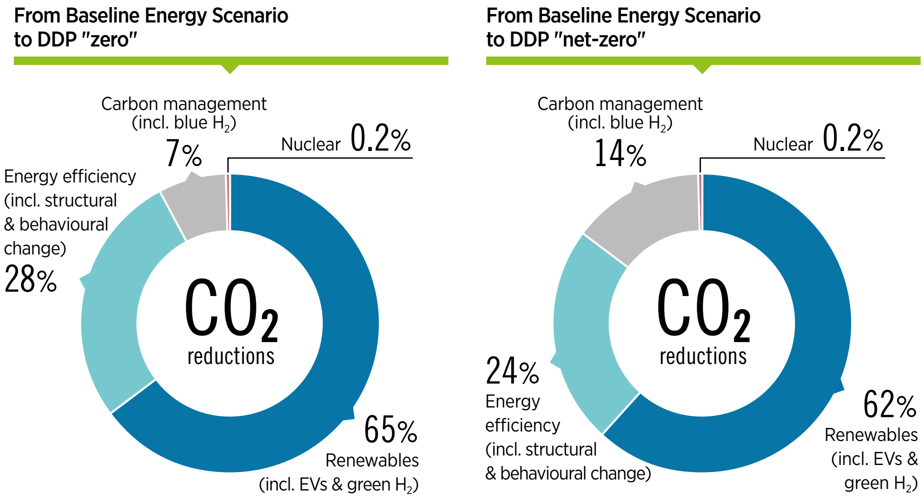
Figure 5.4 looks more broadly at how emissions are reduced from the Baseline Energy Scenario to zero. It shows the relative contributions in four categories:

1) **Renewable energy**, including direct uses of renewable energy (*e.g.*, biofuels, solar thermal), renewable power and both direct (*e.g.*, EVs, heat pumps) and indirect electrification (*e.g.*, green hydrogen, synthetic fuels);
2) **Energy efficiency**, including structural changes (*e.g.*, circular economy, modal shifts) and behavioural changes (*e.g.*, flying less);
3) **Carbon management solutions**, including CDR (*e.g.*, reforestation, direct air capture), bio-energy with carbon capture and storage (BECCS), CCS, and carbon capture, utilisation and storage (CCUS) (including blue hydrogen); and
4) **Nuclear energy**.

In both the Deeper Decarbonisation Perspective "zero" and "net-zero" approaches, around two-thirds of CO_2 emissions are from renewable energy, around one-quarter are from energy efficiency, and the remainder are from carbon management, with a small additional share from nuclear energy.

Figure 5.4 CO_2 cuts with renewables: Two-thirds of the way to zero

Contribution of energy and industrial process-related CO_2 emission reductions from the Baseline Energy Scenario to the Deeper Decarbonisation Perspective "zero" (left) and "net-zero" (right) approaches (%), 2020-2060

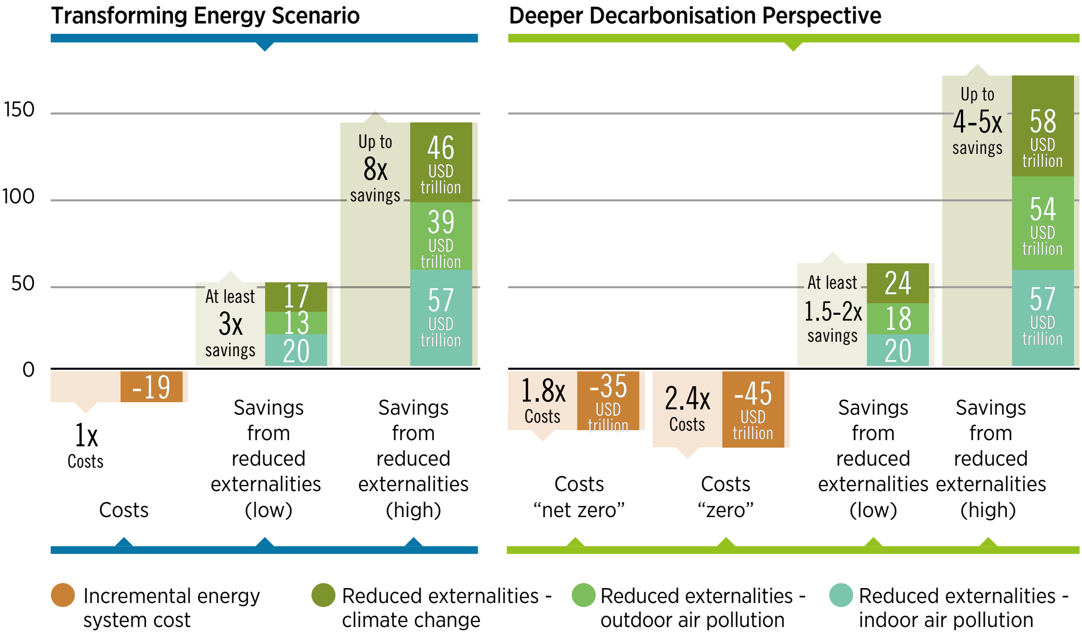


The costs for reducing emissions vary, but overall costs are lower than the savings that result from reduced externalities. In the Transforming Energy Scenario, every USD 1 spent for the energy transition would bring a payback of between USD 3 and USD 8 (Figure 5.5). Or, in cumulative terms, the Transforming Energy Scenario would have an additional cost of USD 19 trillion over the period to 2050 but would result in a payback of between USD 50 trillion and USD 142 trillion in reduced environmental and health externalities.

The Deeper Decarbonisation Perspective would cost an additional USD 16 trillion to achieve net-zero emissions, or an additional USD 26 trillion to achieve fully zero emissions (with no carbon offsets). Therefore, the total additional costs to reach zero range from USD 35 trillion to USD 45 trillion. Yet these higher costs are still much lower than the USD 62 trillion to USD 169 trillion in savings from reduced externalities that would result from reaching zero emissions.

Figure 5.5 Every USD 1 spent brings USD 3-8 payback in environmental and health returns

Cumulative costs and savings for the Transforming Energy Scenario and the Deeper Decarbonisation Perspective "zero" and "net zero", 2020-2050 (TES), 2020-2060 (DDP) (trillion USD_{2015})



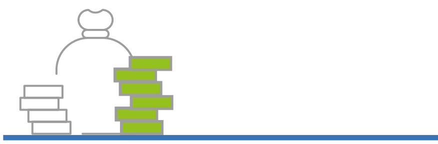
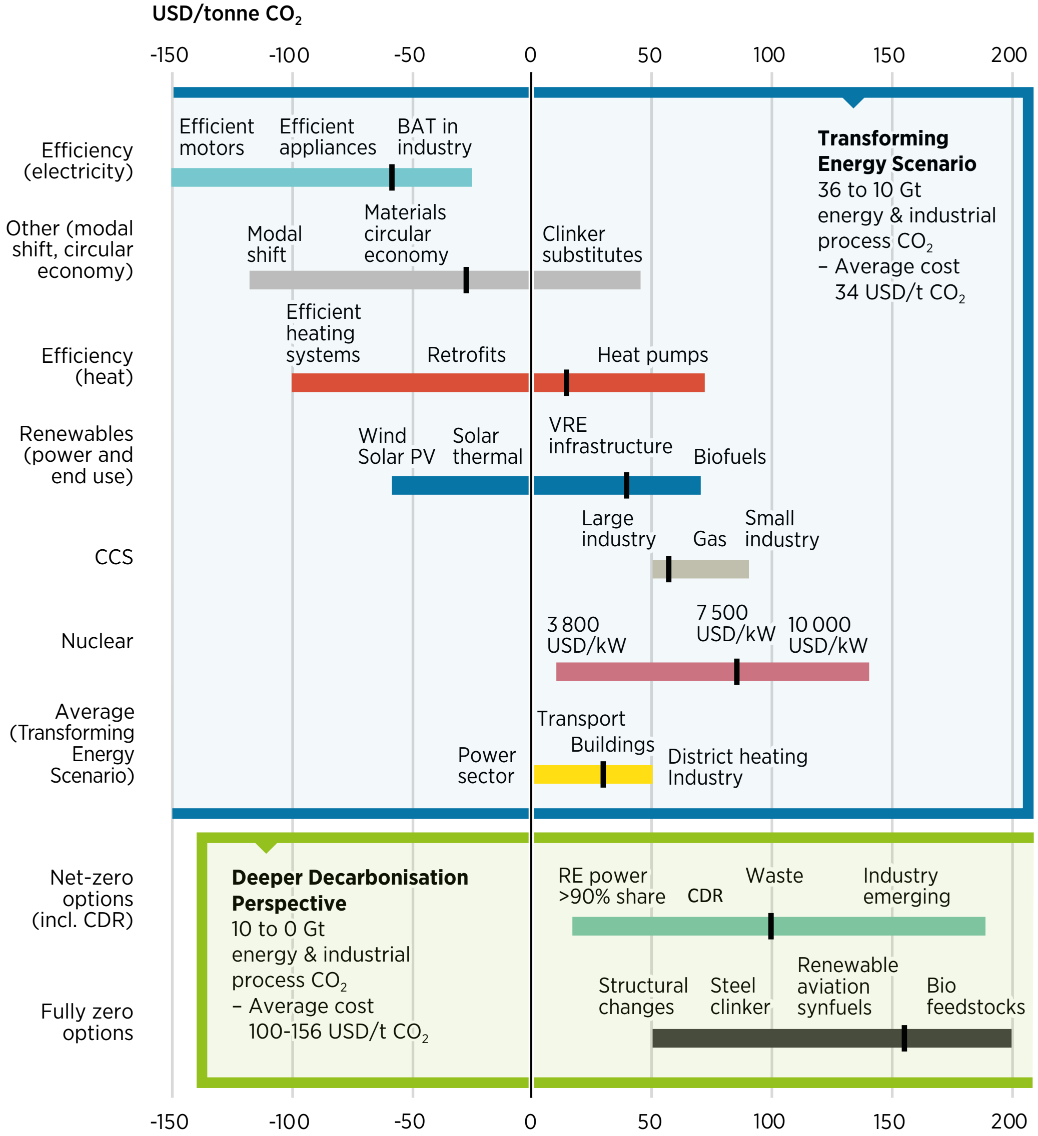


Figure 5.6 Affordable CO_2 mitigation: Efficiency, renewables and structural change
Mitigation costs for select technologies and groupings, 2050



The overall costs do not account for the fact that many of the technologies presented in this report are much cheaper than fossil fuel alternatives, as can be seen in Figure 5.6. Mitigation costs measure the cost at which a tonne of CO_2 can be avoided, or reduced, by another zero-carbon technology. For energy efficiency measures for electricity, the mitigation costs fall in the USD -150/tonne to USD -20/tonne range. Heating efficiency measures range from USD -100/tonne to USD +70/tonne. The mitigation costs of most renewables are between USD -50/tonne and USD +50/tonne (even when including infrastructure costs). These numbers are lower than the costs for CCS, which range from USD +50/tonne to USD +80/tonne, or for nuclear, which averages USD +80/tonne.

Another way to look at it is in the cost to mitigate one tonne of CO_2 over the period. For the Transforming Energy Scenario, which reduces annual emissions to 10 Gt by 2050, the cost would be USD 34 per tonne of CO_2. The Deeper Decarbonisation Perspective, which reduces the remaining emissions to zero, has higher costs. For the "net-zero" approach, the cost is USD 100 per tonne of CO_2, but for the "zero" approach it is USD 156 per tonne of CO_2.

Figure 5.7 Mitigation costs under different scenarios: From USD 23 to USD 156 per tonne of CO_2
Cumulative mitigation costs, cumulative CO_2 reductions and average mitigation costs for the period to 2050 for the Transforming Energy Scenario, and to 2060 for the Deeper Decarbonisation Perspective

	Cumulative costs (USD trillion)	Additional costs for the DDP (USD trillion)	Cumulative CO_2 reduced (Gt)	Average mitigation cost (USD/t CO_2)
Transforming Energy Scenario	19		559	34
Deeper Decarbonisation Perspective "net zero"	19 + 16 (total 35)	16	165	100
Deeper Decarbonisation Perspective "zero"	19 + 16 + 10 (total 45)	26	165	156

5.2 Eliminating the remaining emissions including in challenging sectors such as industry and transport

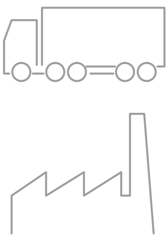
OVERVIEW

As the analysis presented above shows, reaching "net zero" or "zero" requires further action in several sectors. The following sections describe the options to achieve that, as well as some of the challenges remaining.

The power sector would need to move to full deployment of zero-carbon electricity sources. That implies most power systems shifting to very high shares of renewables (90% plus, with some reaching 100%). Section 5.3 outlines how some countries are approaching that challenge.

New clean energy vectors such as hydrogen and its derivatives will play an important role. Section 5.4 discusses how the role of hydrogen could grow. **CCUS also has a role to play,** as discussed in Box 5.1.

However, for some sectors the current options are limited and the optimum pathway to remove emissions is uncertain. These sectors are sometimes called **"hard-to-decarbonise"** or **"hard-to-abate"** sectors and are discussed below and in sections 5.5, 5.6 and 5.7.



REDUCING EMISSIONS IN CHALLENGING SECTORS

This report classifies certain transport and industry sub-sectors as challenging sectors in which to reduce emissions. Some have energy service needs that require high-temperature heat or high energy density, which can be difficult to supply with electricity. Some, like the petrochemical sector, also need feedstocks to produce end-products. And some processes, such as making cement clinker or steel, produce CO_2 emissions. While the Transforming Energy Scenario has already assumed significant growth in solutions in these sectors to reduce emissions – such as direct electrification with renewables, bioenergy, hydrogen and synthetic fuels – additional innovative solutions will be necessary to reduce emissions. Many of these solutions are either costly or still in the early stages of technology deployment, and are not yet ready at scale.

Figure 5.8 details the remaining CO_2 emissions in the Transforming Energy Scenario. In the industry sector, the largest remaining emitters are in cement, chemicals, and steel and iron, followed by aluminium. In transport, the largest remaining emitters are freight (from a combination of road, rail and shipping followed by aviation) and passenger road transport.

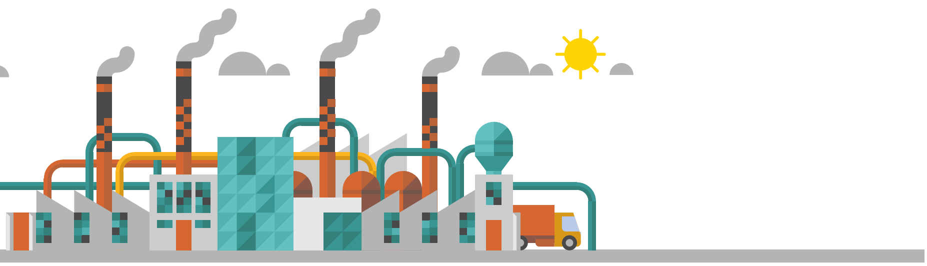
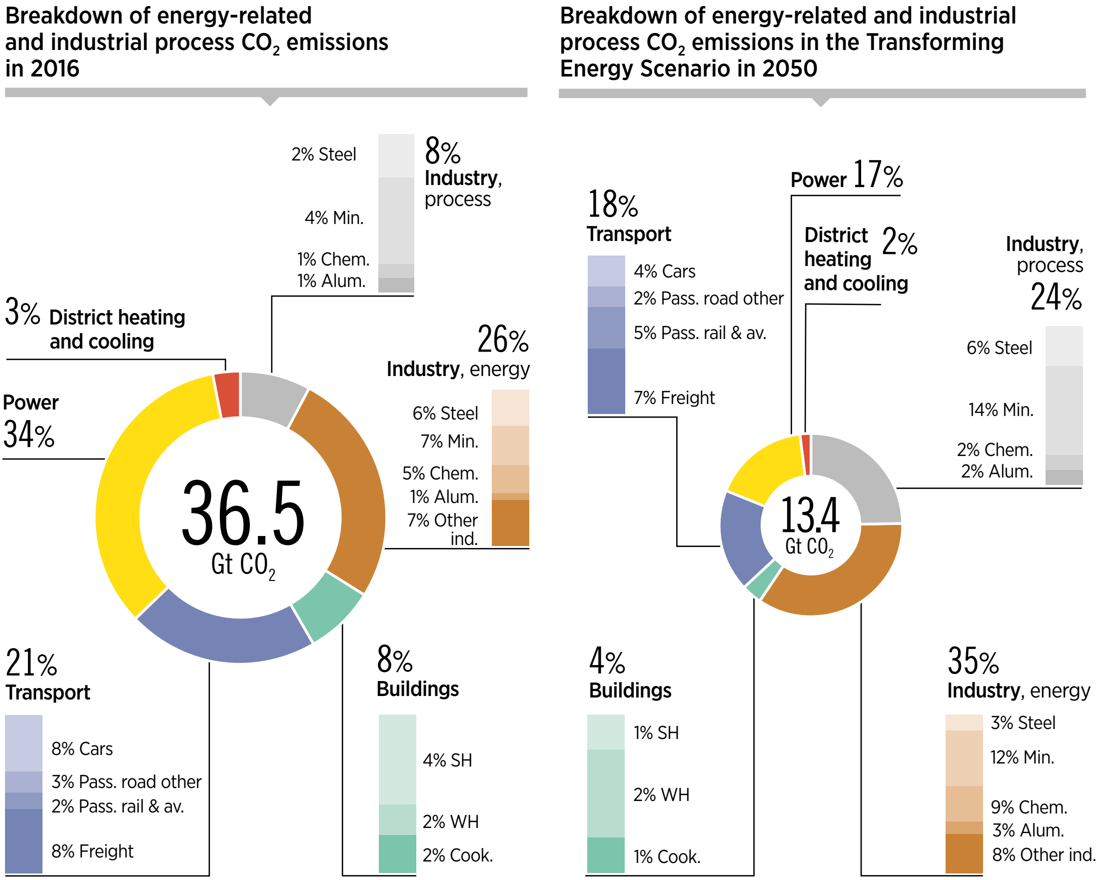


Figure 5.8 CO_2 emissions from industry: Two-thirds of the remainder in the Transforming Energy Scenario



Note: Steel = Iron and steel, Min. = non-metallic minerals (*e.g.* cement), Chem. = chemicals, Alum. = aluminium, Other Ind. = other industry sectors, SH = space heating, WH = water heating, Cook. = cooking, Cars = passenger cars, Pass. road other = passenger road excluding cars (*e.g.* buses, two-three wheelers), Rail & Av. = passenger rail and aviation, Freight = all freight modes, Power = electricity generation

As explained earlier, there remains 9.8 Gt of energy-related CO_2 emissions in the Transforming Energy Scenario, with the bulk of those emissions coming from non-electricity energy sources. In addition, there is 3.6 Gt of CO_2 emissions from industrial processes in 2050, the bulk of which come from the cement and iron/steel sectors. In the Transforming Energy Scenario, CCS and CDR are assumed to reduce this 3.6 Gt by about 2.0 Gt/yr, with an additional 0.7 Gt/yr that can be reduced through materials efficiency and the circular economy. That would leave 0.9 Gt/yr of process emissions that are still emitted into the atmosphere in 2050. Of the combined energy and industrial process emissions remaining in the Transforming Energy Scenario, 70% would come from the industry and transport sectors.

The sectors discussed in this section broadly include the following areas:

- **Specific transport modes**, namely road freight transport, aviation and shipping;
- **Energy-intensive industries**, namely iron and steel, aluminium, chemicals and petrochemicals, and cement;
- **The gas system** – the current systems for transport, transmission and distribution of natural gas.

Table 5.1. Key decarbonisation solutions by sector

Sectors	Key solutions
Road freight transport	Direct electrification, green hydrogen, biofuels
Aviation	Biofuels, synfuels from green hydrogen, electrification
Shipping	Synfuels from green hydrogen, biofuels, electrification
Iron and steel	Green hydrogen, CCS, biomass, circular economy
Chemicals and petrochemicals	Biomass, green hydrogen, circular economy
Aluminium	Electrification, circular economy
Cement and lime	CCS, circular economy, renewable energy and waste
Greening the gas system	Green hydrogen, synthetic methane from green hydrogen, cleaned biogas

In addition, opportunities exist to reduce emissions through action on energy efficiency and greater use of the principles of the circular economy. The circular economy includes recycling, reuse, materials substitution, more efficient materials design and the use of sustainable biomass resources. The most common example of the circular economy is recycling. Another option is reusing the parts of a good after consumer use. Alternatively, the worn parts of a good can be repaired or remanufactured before turning them into new end-products (re-use).

Circular flows reduce the need to extract primary resources, reduce the need to dispose of waste and reduce energy needs. For example, recycling of materials is often more energy efficient than the production of primary materials from natural resources. A reduction of 50% or more of energy and resource use can be achieved for many sectors and products (Gielen and Saygin, 2018). In addition, the same material can be recycled several times without losing quality properties.

Examples of how the circular economy can help reduce emissions in certain industrial sectors are widespread. More efficient use of materials and greatly increased recycling and reuse within a more circular economy could reduce primary production and emissions by as much as 40% globally – and more in developed economies – with the greatest opportunities in plastics and metals. A circular steel economy can reduce the use of natural gas, coal and coke, and a shift to a circular plastics economy can reduce petrochemical use.

Box 5.1 CARBON CAPTURE, UTILISATION AND STORAGE

The technical potential of carbon capture, utilisation and storage (CCUS) is significant in some parts of the world, but progress has been slow. Development of CCUS has been hampered by the high mitigation cost, the lumpiness of investments, technological setbacks, NIMBY (not in my backyard) concerns and uncertainties regarding long-term policy commitments. In the Transforming Energy Scenario, CCUS plays only a limited role. However, for certain industrial processes, such as cement clinker making and waste incineration plants, no other major mitigation option is currently on the table. For others, such as steel making and some chemical processes, CCUS may be cost-competitive compared to other mitigation measures. Therefore, CCUS warrants further development for certain applications.

The use of bioenergy in combination with CCUS also offers the prospect of negative emissions. The Drax Power Station in the UK has started carbon capture from biomass burning, but on a small scale. The hope is that the Drax pilot project, which is capturing one tonne of CO_2 a day, will pave the way for a large-scale rollout of the technology, which could eventually pull 10 Mt a year of CO_2 out of the power plant's smokestack. However, the pilot under way at the North Yorkshire facility is not currently storing any CO_2 (FT, 2019).

MAKING PROGRESS IN CHALLENGING SECTORS

Later sections of this chapter discuss specific sectors, but there are number of general principles and trends that apply across many of the sectors. In summary, realising the progress envisioned in the Deeper Decarbonisation Perspective will require urgent, sustained, multilateral action on multiple fronts. In particular, closer collaboration between industry and a broad range of governments, aided by international bodies, is needed to achieve the following:

Develop a deep evidence base to inform decisions on technology pathways:

- Potential solutions are slowly emerging in most sub-sectors, but significant technology uncertainty remains, and the optimum pathways are not yet self-evident.
- Greater clarity is needed urgently now, in the 2020s, because a massive and rapid ramp-up of deployment will be needed in the 2030s and 2040s.
- A significant increase in demonstration and pilot projects is needed in a diverse range of countries to gather evidence on what is feasible and optimum and to inform key decisions to be made in the 2020s. Learnings from those projects should be shared widely.

Take immediate action on energy efficiency, on reducing energy intensity and on the circular economy:

- Improved energy efficiency and the efficient use of resources is a no-regret strategy and applies to all sectors. Attention to energy efficiency must be coupled with systemic analysis of opportunities to reduce energy intensity.
- Greater attention needs be given to life-cycle and circular economy analyses for specific sectors, exploring strategies for recycling, materials efficiency, materials substitution, etc.
- Policies to promote energy efficiency, such as minimum energy performance standards and integrated resource planning, as well as policies to enable reductions in energy intensity, should be applied more aggressively. More directive policy tools such as technology-forcing regulations will likely also be needed in some cases.

Innovate to drive down the cost of a range of solutions:

- The costs of potential decarbonisation solutions vary widely; however, on average the costs are above the costs of the measures in the Transforming Energy Scenario.
- Increased support is needed for innovation across the innovation chain (research, development and demonstration) including taking a systemic approach to innovation where technology development is partnered with innovations in business models and changes in the way processes operate, and is enabled by innovative approaches to policy and market design.
- Cost reduction is driven by both innovation and scale-up. In the short term, deployment will be limited, but encouraging early adoption in niche or selected markets can assist in building scale and reducing costs.
- Some of the promising pathways for decarbonisation are innovative with supply chains and manufacturing processes. For example, shifting iron ore processing to regions with readily available renewable electricity, and using the direct reduced iron (DRI) process, could lead to reductions in China's iron and steel CO_2 footprint.

Explore international approaches to certification and regulation:

- Green products and energy carriers will require certification systems, to enable development of markets and ensure sustainable sources, etc.
- Global approaches will be needed to facilitate cross-border trade and to build economies of scale.

Develop policy measures to incentivise investment:

- Credible long-term policy signals are needed to mobilise the necessary investments.
- Global sectoral approaches are ideally needed to ensure a level playing field. Past attempts have struggled, and new approaches (*e.g.*, carbon border tax) need to be explored in detail by front-running countries and regions.

Focus on the outcomes needed, not the existing processes:

- The goal is to meet the industrial need while removing carbon emissions from a wide variety of processes. Each industrial process is unique, and the solutions may need to be too.
- Imaginative approaches exist that are not yet being explored, and others can likely be created if the problem is viewed from the right angle. Examples include: ammonia as a shipping fuel; wood in construction; biorefineries co-producing biomaterials and energy; biomass with CCS in cement kilns, etc.
- The specifics of the industrial need must be analysed, in close collaboration with industry experts, to creatively explore how the goal can be achieved in a different, low-carbon way.

Identify pressure points for global change:

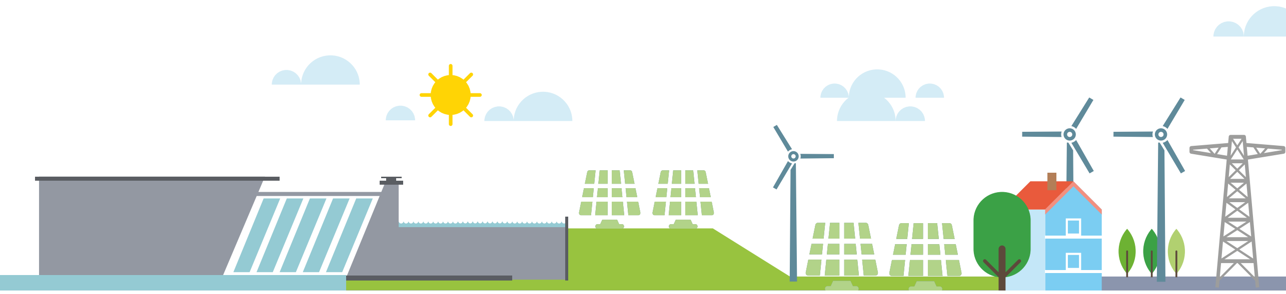
- A handful of specific and well-defined opportunities exist to make an early but significant difference, and can help build confidence and scale.
- Defining an optimal low-carbon pathway for all shipping worldwide, for example, is a major task, but assessing alternatives that could be implemented in a single shipping route from China to Europe via Singapore alone is more manageable.
- Other examples include:
  - Singapore loads about one-fifth all fossil fuels used for shipping.
  - China accounts for over half of today's iron and steel production.
  - Very large trucks (> 15-tonne weight capacity) are responsible for over 75% of total freight truck CO_2 emissions.

5.3 Very high shares of renewable power

The Transforming Energy Scenario documents the need for the power sector to take a decisive and rapid turn to renewables in order to achieve the Paris Agreement goals. Meeting these goals in the power sector will require large increases in global renewable power investment, accelerating the phase-out of fossil fuel use for electricity generation, and strong policy support.

In the Transforming Energy Scenario, the power sector sees a significant transformation, reaching an 86% renewable energy share in electricity generation by 2050, up from 26% in 2018. In this scenario, many countries have renewables shares above 95% by 2050, with some at 100% (for details see Box 1.3). However, power sector emissions are still at around 2 Gt in 2050 and will need to be reduced to zero.

Fortunately, the path forward for the power sector is emerging. Renewable energy can provide the bulk of power supply. The technologies are available and market-proven, the costs are modest, and the policy tools are well-documented and effective. Reducing the sector's emissions to zero can be achieved through full deployment of zero-carbon electricity sources, almost entirely renewable energy. Many countries are already starting to show how power systems can operate with very high shares of variable renewable energy (Enerdata, 2019; Hill, 2020), and over the coming decades this will increasingly become the norm. It is therefore crucial that countries share experiences and knowledge.



Box 5.2 INNOVATION TO SUPPORT HIGH SHARES OF VARIABLE RENEWABLE POWER

A number of countries, such as Uruguay and Costa Rica, already have very high, approaching 100%, shares of renewable energy in their power systems, and a growing number of countries aspire to follow suit. Sweden, for example, has a policy objective of 100% renewable power by mid-century. IRENA, in collaboration with the Swedish Energy Agency, has applied its innovation framework for the power sector transformation (elaborated in the report *Innovation landscape for a renewable-powered future* (IRENA, 2019o)), to the case of Sweden. The project assessed which innovative solutions could help Sweden achieve its ambitious policy target by 2040. By combining innovations in enabling technologies, business models, market design and system operation, the project developed four solutions for integrating high shares of VRE into the Swedish power system (Figure 5.9).

While each combination of innovations offers a solution for certain segments of the power sector's value chain, a holistic approach to these solutions creates major system-wide flexibility options, including direct and indirect electrification of end-use sectors (transport, buildings and industry) with renewables, long-term hydrogen storage and the provision of innovative grid services from various assets, such as batteries, electrolysers and EVs via smart charging technologies. Best practices in VRE integration were also collected and considered in the analysis. Overall, these experiences, together with the essential infrastructure for a decarbonised power system in place, indicate that obtaining a 100% renewable power system in Sweden with an increasingly higher share of VRE, from 11% today up to over 42% (39% wind, 3% solar PV) by 2040, is achievable. →

Box 5.2 (continued)

Figure 5.9 Four innovative solutions for Sweden's power system

Solution I

Enabling technologies

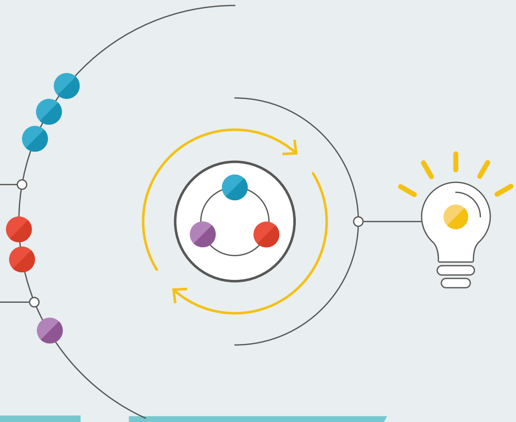
- Utility-scale batteries
- Internet of Things
- Artificial intelligence and big data

Market design

- Increasing time granularity in electricity markets
- Innovative ancillary services

System operation

- Advanced weather forecasting of variable renewable power generation



- ▸ Provides innovative ancillary services both from conventional and variable renewable energy sources;
- ▸ Ensures the security and stability of the power system and the provision of new ancillary services, including frequency and voltage support from VRE sources;
- ▸ Enables the provision of such ancillary services with the help of more precise solar and wind power generation forecasts.

Solution I

Innovative ancillary services from both conventional and variable renewable energy sources

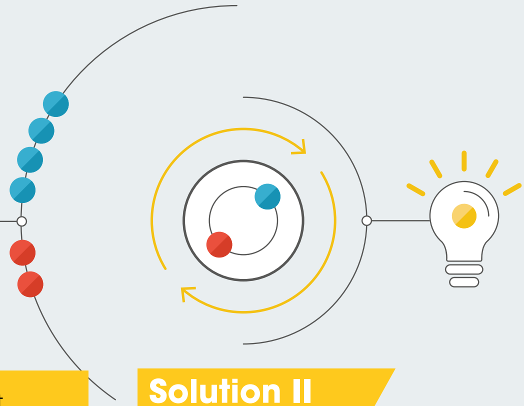
Solution II

Enabling technologies

- Internet of Things
- Artificial intelligence and big data
- Blockchain
- Supergrids

Market design

- Increasing time granularity in electricity markets
- Regional markets



- ▸ Improves flexibility in the existing pan-European market design;
- ▸ Fosters collaboration among system operators in Sweden, the Nordic, Baltic and wider European region;
- ▸ Ensures clear and effective division of responsibilities to manage an increasingly complex, decentralised and digitalised power system.

Solution II

Pan-European market as flexibility provider with effective collaboration among system operators

Source: IRENA (2020c)

Solution III

Enabling technologies

- Behind-the-meter batteries
- EV smart charging
- Renewable power-to-heat
- Internet of Things
- Artificial intelligence and big data
- Blockchain

Business models

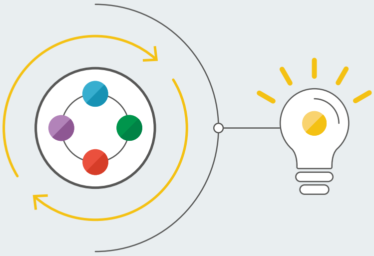
- Aggregators

Market design

- Time-of-use tariffs
- Innovative ancillary services
- Market integration of distributed energy resources

System operation

- Future role of distribution system operators
- Co-operation between transmission and distribution system operators
- Virtual power lines



- ▸ Aggregates distributed energy resources to optimise distribution system operation;
- ▸ Balances supply and demand daily;
- ▸ Manages network congestion at the distribution level in the context of wind shortage/surplus in the short term, until transmission projects with long lead times are implemented.

Solution III

System-friendly integration of distributed energy resources

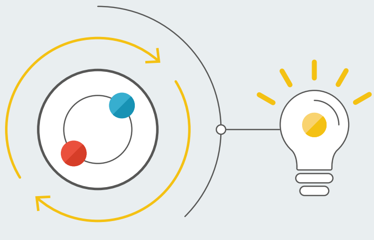
Solution IV

Enabling technologies

- Renewable power-to-heat
- Renewable power-to-hydrogen
- Artificial intelligence and big data

Market design

- Increasing time granularity in electricity markets
- Innovative ancillary services
- Regional markets



- ▸ Decarbonises end use sectors such as direct heat and transport via electrification with renewable energy sources;
- ▸ Enhances flexibility and helps maintain system stability via direct and indirect electrification via power-to-X technologies (such as renewable power-to-heat and renewable power-to-hydrogen);
- ▸ Is part of a truly complex, yet disruptive solution, for sectors that are difficult to eliminate emissions completely, such as iron and steel industries.

Solution IV

Decarbonisation of end-use sectors via electrification with renewable energy sources

5.4 The role of hydrogen

Although hydrogen is not a primary energy source, it can be produced from fossil fuels either without CCS (grey hydrogen) or with CCS (blue hydrogen), or from renewable power through electrolysis (green hydrogen). Hydrogen is already an industrial commodity, and currently around 120 Mt per year of grey hydrogen is produced and consumed, mostly in the refining industry and for the production of ammonia. Dedicated hydrogen pipelines have been in operation for decades. Although hydrogen production is already "at scale", it is not yet clean; today 96% of all hydrogen is produced from fossil fuels and the remainder from electrolysis, mainly in the chlor-alkali process.

As this report shows, electrification of half of all final energy use is possible by 2050 in the Transforming Energy Scenario. Of this, roughly 85% is consumed as electricity directly, and 15% is renewable electricity used to produce green hydrogen (representing around 5-6% of TFEC). Of the remaining half of final energy, one-third is provided by direct use of renewables. But even with this significant scale-up of renewable electricity, green hydrogen and direct uses, there remains one-third of energy demand whose related emissions will eventually need to be addressed – and here green hydrogen can play an expanded role.

Green hydrogen is currently more expensive than conventional hydrogen production from fossil fuels (grey hydrogen). However, the cost of green hydrogen is falling rapidly due to the combined effects of reduced electrolyser cost and cheaper renewable power, to the point where it can compete with blue hydrogen in the near future (see Figure 5.10).

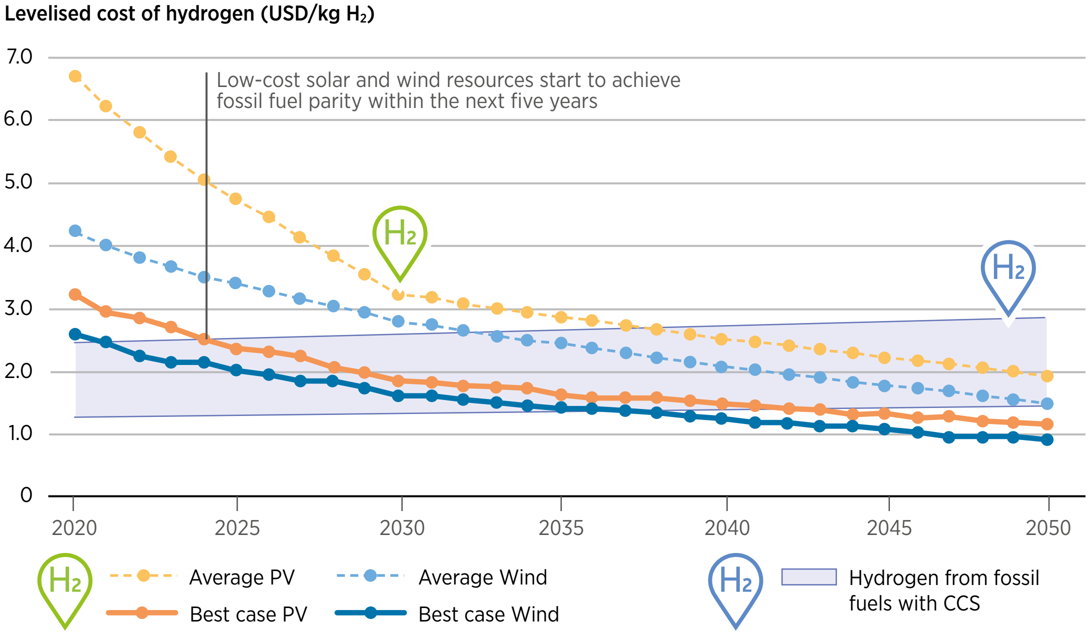
The cost of renewable power (used to make the green hydrogen), the cost and performance of electrolysers, and the electrolyser load factor determine the green hydrogen production cost. Production costs of around USD 2-3 per kilogram for green hydrogen are feasible in the coming decade in the best locations. Low cost can also be achieved earlier at locations with good renewable energy resources.

Green hydrogen production also has the potential to create a virtuous cycle for renewables-based electricity grids, as hydrogen can provide much-needed flexibility to power systems, acting as a buffer to non-dispatchable renewable generation, and has a potential role for seasonal balancing of renewable generation by storing large amounts of hydrogen in salt caverns and other underground reservoirs.

As a consequence of the potential for low-cost green hydrogen, certain energy-intensive industries may in the future be located at sites that meet such criteria. A potential boom of renewables and green hydrogen in Australia may be one example, as the country has announced two feasibility studies to explore renewable ammonia at commercial scale (Paul, 2019). In Norway, the first plant producing ammonia from green hydrogen is expected to open in 2020 (Yara, 2019). Iron making may follow later.

In the Transforming Energy Scenario, hydrogen has the potential to supply nearly 29 EJ of global energy demand by 2050. Two-thirds of that would come from renewable sources, requiring at minimum around 7 500 TWh of renewable electricity, roughly equivalent to 30% of global electricity generation today.

Figure 5.10 Green hydrogen production costs: Approaching competitiveness with blue hydrogen
Hydrogen production costs from solar and wind vs. fossil fuels with carbon capture and storage, 2020-2050



Note: Electrolyser costs: 770 USD/kW (2020), 540 USD/kW (2030), 435 USD/kW (2040) and 370 USD/kW (2050). CO_2 prices: USD 50 per tonne (2030), USD 100 per tonne (2040) and USD 200 per tonne (2050).

Hydrogen is already employed in industry in significant quantities; however, this grey hydrogen will have to be replaced by a combination of blue and green hydrogen. There is significant potential to reduce emissions in chemicals, refining, and iron and steel using green hydrogen to replace fossil fuel-based feedstocks and to provide high-temperature heat. In the Transforming Energy Scenario, just under 14 EJ of renewable hydrogen would be consumed in the industrial sector in 2050, mainly in the iron and steel industry, in chemicals and also for ammonia production.

The transport sector would be the second largest user of renewable hydrogen with 4 EJ consumed per year by 2050. In the transport sector, hydrogen can be used in fuel cell electric vehicles (FCEVs), mostly for heavier freight transport, or to produce synthetic fuels for shipping or aviation. In the buildings sector, hydrogen can be blended with natural gas or used to produce synthetic methane and injected in gas grids, although this application is limited to around 1 EJ.

Green hydrogen can be processed further into hydrocarbons, also known as synthetic fuels or e-fuels. With the exception of synthetic ammonia production, synthetic fuels play a limited role in the Transforming Energy Scenario, but they will need significant scale-up when the remaining one-third of energy needs to reduce emissions to zero. In an earlier brief, IRENA outlined activity in the shipping sector to explore the use of fuels produced from hydrogen (IRENA, 2019r). The aviation sector is also looking into e-fuels as a possible solution – in addition to advanced biofuels (bio-jet).

The natural gas industry is also looking at hydrogen as a promising solution for greening the gas system, extending the life of existing infrastructure (see section 5.7). Some view the gas grid in this scenario functioning as a large-scale storage asset, accommodating and distributing low-cost renewable electricity. Projects are being developed in the Netherlands, the UK, Northern France and Italy. However, more work needs to be done, and barriers related to economics and standards must be overcome.

It is important to consider scale. Even the installation of 50 GW of electrolysers, 330 times more than are in operation today, would still only allow the production of enough fuel to provide 10% of global shipping's energy needs. To produce the 19 EJ of green hydrogen in the Transforming Energy Scenario, much more capacity than this would be needed – around 1 700 GW of electrolysers by 2050 – and despite this growth, green hydrogen would still only provide around 5-6% of global final energy. Blue hydrogen could provide an additional 2.5% of global final energy, for a total of all hydrogen in the 7-8% range.

In a scenario where global emissions reach zero, hydrogen could be the missing link in the transformation of the global energy system. The Deeper Decarbonisation Perspective presented in this chapter outline some ways in which hydrogen, and hydrogen based-fuels, can play a larger role beyond the Transforming Energy Scenario – specifically in industry, transport and the buildings sector. In the long run, hydrogen could become a key element in 100% renewable energy systems (IRENA, 2018c; Butler, 2020). In such a case, as more and more electrolysis is deployed, as well as with more renewables, green hydrogen will increasingly become more cost-competitive. The current drive towards the hydrogen economy has a remarkable momentum and a wide scope. Today's role of clean hydrogen is modest, but the growth potential is significant.

5.5 Challenging sectors: Transport

Transport accounts for around one-quarter of global energy-related CO_2 emissions. The path forward to provide transport services while reducing CO_2 emissions is becoming clear for some, but not all, transport modes. For light-duty vehicles (cars, sport-utility vehicles and small trucks), battery electric vehicles have shown dramatic improvements in range (kilometres per charge), cost and market share. The path forward here is clear: electrify the light-duty vehicle fleet and provide that electricity from renewable sources. For other modes, the path is less clear, although there is significant untapped potential for sustainable liquid biofuels. Additional solutions will be needed for road freight transport, aviation and shipping. Potential solutions in these transport modes are described in the following sub-sections.

ROAD FREIGHT TRANSPORT

Currently, freight transport (trucks, ships and trains) represents more than 40% of transport's total energy demand. That demand is projected to increase by 20%, from 25 EJ in 2016 to 30 EJ in 2050. In the Planned Energy Scenario, emissions from all modes of freight transport will increase to 3.8 Gt per year by 2050. In the Transforming Energy Scenario, freight's CO_2 emissions would decline by almost 75% compared to the Planned Energy Scenario, to just under 1 Gt of CO_2 annually by 2050. Around 0.6 Gt per year of reductions would come from the use of biofuels in trucks and ships. Another 1.5 Gt of CO_2 emissions could be cut by efficiency measures across all modes of freight transport, and the remainder of reductions could come from switching to electricity, especially for freight trains and delivery trucks.

Several technologies that are being developed are potential options for reducing emissions to zero in road freight transport. Plug-in battery EVs and fully electric trucks could account for the majority of commercial light-to-medium duty trucks that typically travel 100 to 200 kilometres per day. Battery technology continues to improve, and a recent study (UCS, 2019) shows that already 27 manufacturers are offering 70 different models of electric trucks in the United States alone. Many are developing and implementing lithium-ion technology in delivery vans and semi-trucks for use by logistics companies.

While the main trend in delivery trucks seems to be towards EVs, the outlook is not as clear for heavy-duty trucks. Some manufacturers are planning to provide battery-electric heavy-duty trucks, and some also are considering alternative fuels that can also reduce emissions. Hydrogen is one option, but it may be less competitive if battery performance improves rapidly. Also being considered are electric highways, which use overhead catenary lines to power heavy-duty trucks over long distances. Those trucks would then use battery power for the shorter travel to regional distribution centres.

Alternative options could be producing synthetic fuels, or e-fuels, that can be used in internal combustion engines, or the use of clean biogas (biomethane) and conventional and advanced liquid biofuels. Biofuels are already being commercialised for trucks in some countries, but major barriers to widespread production and adoption remain (IRENA, 2019m).

AVIATION

Aviation, and jet fuel use in particular, is one of the fastest-growing sources of greenhouse gas emissions. Emissions from aviation are around 0.9 Gt of CO_2 per year, or 2-3% of global emissions, and the figure is higher if upstream emissions in fuel production and non-CO_2 greenhouse effects are considered. By 2050 in the Planned Energy Scenario, emissions would increase to 2.1 Gt/yr, whereas in the Transforming Energy Scenario they decline to around 0.7 Gt, despite an expected increase in passenger activity of more than 200%.

There are four main ways to deliver net-zero aviation: develop new electric aircraft, produce drop-in fuels (including bio-jet), change the fuels of existing aircraft (for instance to synthetic fuels) and take the emissions out of the atmosphere.

Aviation emissions can be reduced by 1.5% annually through improved fuel efficiency in new aircraft, aircraft modifications, airport restructuring and optimised navigational systems (IRENA, 2017c). However, a significant longer-term reduction in emissions would require airlines to use more fuels that are renewable and sustainable, such as biofuels developed for jet aircraft. Although sustainable and clean alternative propulsion technologies are in development, such as electric- or solar-powered aircraft for long-distance flights, synthetic fuels or even cryogenic hydrogen as a fuel, these options are unlikely to be ready for commercial use until later in the century.

Biofuels for jet aircraft, known in the industry as bio-jet, are therefore the only currently available option to achieve significant reductions in aviation emissions. In the Transforming Energy Scenario, liquid biofuel production overall would increase five-fold from 130 billion litres in 2016 to 652 billion litres in 2050, and over 100 billion litres of bio-jet would be consumed in the aviation sector (IRENA, 2017d). This, in addition to efficiency and operational improvements, would be the main reasons for the reductions in CO_2 emissions in the Transforming Energy Scenario.

Although the market for bio-jet is currently very limited, and price information is also limited, bio-jet use is likely to grow rapidly in the coming decades. However, its widespread use will depend on a supportive regulatory framework and/or on significant carbon pricing. Widespread use will also require longer-term cost reductions, which are critical to close the gap with conventional jet fuel. Emissions reductions in aviation are challenging, but they are necessary for the full decarbonisation of the transport sector.

In addition to bio-jet fuel, research is exploring the production of synthetic jet fuel using green hydrogen. In particular, a project at Rotterdam's Innovation Campus is combining highly innovative technologies to produce jet fuel made (partly) from CO_2 to help achieve a carbon-neutral future for the aviation sector. The project captures CO_2 from the air and then combines the CO_2 with hydrogen produced by splitting water into hydrogen and oxygen with electrolysis. The result is a synthetic gas that can be transformed into jet fuel. The project is still at the demonstration stage, however. Synthetic jet fuels still have a long way to go before becoming fully competitive, due mainly to their high costs.

SHIPPING

On average, the shipping sector is responsible for around 3% of annual global greenhouse gas emissions. In the absence of suitable mitigation policies, the International Maritime Organization (IMO) estimates that greenhouse gas emissions associated with the shipping sector could grow between 50% and 250% by 2050. In this context, the IMO states that shipping CO_2 emissions need to fall by at least 50% by 2050, compared to 2008 (IMO, 2018).

Despite efficiency gains, and the development of solutions, such as the switch to fossil-based liquefied natural gas (LNG), emissions have continued to rise as trade volumes grow. To reduce emissions, therefore, the shipping sector would eventually need to shift to renewable fuels or alternative means of propulsion.

Alternative fuel options all have different advantages and disadvantages, and there is no consensus on which option is best. Liquid biofuels, renewable hydrogen and other hydrogen-derived fuels such as ammonia, as well as wind and solar applications, are being considered as fuel alternatives. From a technological perspective, liquid biofuels are mature, require few adjustments to the existing engines of ships and port infrastructure, and can have considerable emissions reduction benefits, even as blends. However, three main barriers limit biofuel potential in the shipping sector: economics, availability and sustainability concerns.

Another option is synthetic fuels (electrofuels or e-fuels), which are produced using electricity as the main energy input. The electricity is used to produce hydrogen, which is then combined with CO_2, alcohols or hydrocarbons, or nitrogen in order to produce ammonia. Common synthetic fuels being considered include methanol and ammonia. These fuels can effectively decrease and even eliminate emissions if they are produced from green hydrogen created through electrolysis using renewable power. Most plants producing e-fuels are at pilot scale, although a commercial-sized methanol plant is producing 5 million litres per year in Iceland, and another commercial-scale plant is slated to come online in Norway in 2020.

Waste-based fuels could also play a role. The fuels can be produced using gases from waste treatment processes or flue gas from non-renewable sources, such as steel mill flue gases; or they can be made from waste plastics and/or rubber. These types of fuels are considered to be recycled carbon fuels. Although they are not considered to be renewable, the claimed benefit is that because they recycle gases that would otherwise have been emitted, their use for a secondary purpose would not result in additional emissions. A third pathway is the production of fuels from plastic-to-fuel plants. An estimated 70 million litres per year are currently produced using this method.

Finally, wind and solar power have historically played important roles in the shipping sector. Given the size and weight of today's commercial vessels, wind and solar alone cannot provide the necessary power to move the load of large ships. They can, however, improve overall efficiency by reducing fuel consumption. Yet there are still barriers to the adoption of these technologies in the shipping sector, including surface availability and cargo space limitations for wind, while for solar PV technologies, environmental salinity can be an issue.

The shipping sector may see significant change in the coming years, although the direction remains unclear. This poses both a risk and an opportunity, depending on the direction and magnitude of the change.

5.6 Challenging sectors: Industry

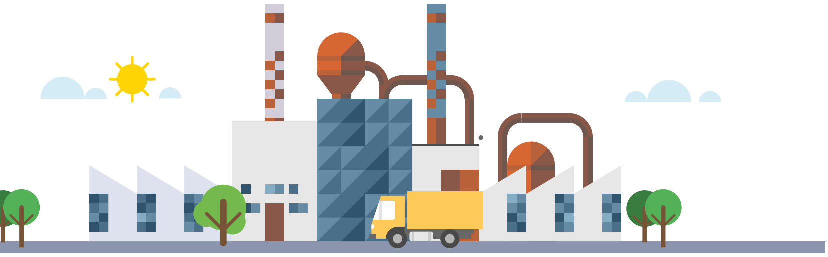
Industry is responsible for over one-quarter of global energy-related CO_2 emissions, and an additional 8% of global CO_2 emissions come from industrial processes within industry. So in total, industry is responsible for around one-third of global energy and industrial process-related CO_2 emissions. A few industries account for the majority of the industry sector's energy use: iron and steel, non-ferrous metals (notably aluminium), chemicals and petrochemicals, and non-metallic minerals (notably cement).

Currently, few economically viable solutions exist for reducing CO_2 emissions at scale in these industrial sectors. While the Transforming Energy Scenario does result in reductions in industrial emissions of 60% by 2050, largely by focusing on low-hanging fruits (such as energy efficiency measures and low to medium temperature process heat), the sector remains the single largest emission source. Therefore, industry will require the development and commercialisation of new zero-emission technology solutions that will drive down emissions not just by 60%, but eventually to net zero.

Over the past few decades, significant progress has been achieved in reducing the industry sector's emissions of substances that deplete the ozone layer, as outlined in the Montreal Protocol, as well as greenhouse gases such as nitrous oxide (N_2O), sulphur hexafluoride (SF_6) and others (UNEP, 2020). This demonstrates that reductions in industrial emissions are possible under the right regulatory conditions.

The dominant remaining industrial greenhouse gas is CO_2. Its emissions can be divided into energy-related emissions from fossil fuel combustion to generate process heat in the form of hot water, steam and direct heat; and process emissions such as those from limestone calcination during the cement-making process. Emissions also arise throughout the life cycles of industrial products, such as fugitive emissions during the use of solvents, lubricants and other compounds, and emissions from post-consumer plastic waste incineration.

This section focuses on options to reduce direct emissions from some key industry sub-sectors related to fossil fuel combustion and industrial processes. All types of low-carbon technologies, including renewable energy, electrification, CCUS and energy efficiency, will play important roles moving forward. But industry also has some unique opportunities related to the choice of feedstocks and product mixes that deserve more attention.



CEMENT AND LIME

Cement is produced by mixing finely ground cement clinker with smaller quantities of other inorganic materials such as gypsum. Cement clinker, in turn, is produced by calcination of limestone. Calcinated limestone is the key component in cement, and calcination is the main energy-consuming process in the cement industry, which makes it very challenging to reduce CO_2 emissions in this industrial sub-sector.

In 2016, the cement industry emitted around 4 Gt of CO_2, with around 2 Gt of that total being process emissions. China is by far the largest producer of cement worldwide, accounting for 57% of global production in 2016, and it also had the largest global lime production in 2017; if India is included then two-thirds of global cement production takes place in just two countries. In the Planned Energy Scenario, the cement industry will increase its total emissions to 4.7 Gt/yr by 2050, as demand for cement increases 25%. In the Transforming Energy Scenario, emissions are reduced to just over 3 Gt/yr by 2050, but the cement sector remains the largest single source of CO_2 emissions in industry.

Cement emissions from clinker manufacture have two main sources: 1) process CO_2 released by the calcination of carbonate minerals (limestones) in the kiln feed, and 2) energy-derived CO_2 released by combustion of the fuels used to heat the kiln feed. Cement clinker is characterised by a high level of process CO_2 emissions due to the large proportion of limestone required for its manufacture and high process temperatures of 1 000 °C or more. The chemical precalciner reaction needed to produce lime results in emissions of around 0.5 tonnes of CO_2 per tonne of clinker that is the result of processing around 1.2 tonnes of limestone for the production of lime. This process results in around 60% of the total CO_2 emissions from cement making.

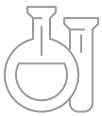
The cement industry is not easy, because reducing CO_2 emissions is challenging due to high process emissions related to the production of clinker. Cement clinker can be substituted with other materials that have similar properties, such as supplementary cementitious metals and alternative cement formulations. Unfortunately, properties and feedstock requirements limit the practical use of the formulations with high CO_2 reduction potentials. In the short term, advanced technological and experimental methods are needed to establish a better understanding of the potential of these alternative cements. These alternative binders could provide a simple yet promising solution for cement clinker replacement if they can compete on cost when deployed at industrial scale. Research and innovation are crucial, since the potential application of novel binder can be fully realised only through detailed investigation and characterisation of binders with the help of cutting-edge technologies.

Emissions can be reduced in cement by other means, including the use of biofuels, waste and other alternatives for process heating, and by efficiency measures resulting from the wide-scale adoption of best practices in cement making, such as efficient motors and grinding.

For these reasons, carbon capture, utilisation and storage warrants discussion for the cement industry, as no other major mitigation option for cement clinker making currently exists. CCUS constitutes a niche application in the Transforming Energy Scenario, limited to a few applications in industry. Nevertheless, there is a need to scale up CCUS to over 2 Gt per year to address CO_2 emissions in a few industry segments, specifically in the cement sector. Further increases in CCUS may be necessary if the cement sector is to reach net-zero emissions. A co-benefit of using CCUS in cement kilns is that it could be combined with biomass combustion that would not only reduce emissions, but also create an opportunity to achieve negative emissions through the use of bioenergy CCS.

Lime is used in a wide range of products, with the largest applications in the iron and steel, pulp and paper, sugar and construction industries. In most industrialised countries, the lime industry consists of a small number of large corporations, while in most developing countries, lime kilns (ovens) are typically small operations using local technology. CO_2 emissions arise in lime production from the decarbonisation of limestone and magnesium carbonate, from fuel combusted in the process and from indirect emissions from electricity consumed in the process. CO_2 emissions reductions can be achieved through the use of more efficient kilns and through improved management of existing kilns using similar techniques to those in the cement industry.

CHEMICALS AND PETROCHEMICALS



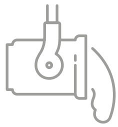
The chemical and petrochemical sector produces products that are derived from fossil fuel feedstocks as well as from other inorganic raw materials. The organic chemical industry is the largest energy-using sub-sector and typically uses a steam cracking process to make olefins (ethylene, propylene and butadiene) from naphtha, ethane, propane or other crude oil-derived feedstocks. In addition to providing raw materials to produce organic chemicals and plastics, fossil fuels are an energy source. In contrast, inorganic chemicals production (*e.g.*, chlorine, phosphate) also consumes energy, but uses much less than the production of organics and often in the form of electricity where emissions take place outside of the sector's boundaries.

In 2015, this industry sub-sector emitted around 2 Gt of CO_2 (including process emissions), and in the Planned Energy Scenario emissions will grow to 2.8 Gt per year by 2050. In the Transforming Energy Scenario, emissions decline to just over 1 Gt using some of the technologies and processes listed in this section.

Chemicals and petrochemical products have wide, consolidated demand today, and most of them could be displaced in alternative ways, such as power-to-chemicals and biomass-based products. Most of the industry's activities (*i.e.*, refineries, ammonia production, bulk chemicals, etc.) rely on hydrogen from fossil fuels, a well-established industry with decades of experience. Hydrogen from renewables thus has the potential to replace fossil fuel-based feedstocks in high-emissions applications. In order to make the synthetic fuels and feedstocks from hydrogen, a source of CO_2 will be needed (or nitrogen in the case of ammonia). Several options exist, but the use of CO_2 from direct air capture or CCUS from bioenergy are two possible sources.

The growth of the petrochemical industry, and especially the surge in the use of single-use plastic that is then usually incinerated, is increasing the difficulty of cutting emissions from the sector (Pooler, 2020). Bioplastics made from renewable sources such as sugar cane or starch are promising sustainable alternatives to traditional plastics.

A complementary option is the circular economy, which includes recycling, reuse, materials substitution and more efficient materials design. However, new economic and financing tools, new regulatory frameworks and even digital marketplaces for the management of a circular economy would be needed to promote and steer its development. Similarly, a societal rethinking will be essential to promote customer interest and to acknowledge the value that can be created by the shift from a linear economy to a circular one.



IRON AND STEEL

Production of iron and steel is one of the largest sources of industrial emissions, representing up to 9% of global fossil fuel CO_2 emitted in 2017. A significant share of the total energy consumed for iron and steel production comes from the use of coal and coke as chemical reducing agents for iron production in traditional blast furnaces that result in CO_2 emissions. Coal and coal by-products represent 78% of the sector's total energy demand (accounting for the energy content of blast furnace and coke oven gases as by-products).

In 2016, the sector emitted a combined total of just over 3 Gt (including process emissions) of CO_2, and under the Planned Energy Scenario this would remain stable. Demand for steel and iron would increase around 15% over the period in this scenario, but advances in manufacturing efficiency and recycling would keep emissions stable. In the Transforming Energy Scenario, emissions would decline to 1.2 Gt/yr by 2050, assuming that some of the following technologies and approaches become more widespread.

The industry is pursuing several key low-emission production routes that would help accomplish further reduction. The first is hydrogen from renewables, which has received increasing attention as an enabler of emissions reductions in the production of iron through the direct reduction of iron ore (IRENA, 2019g). Hydrogen-based iron making is technically feasible (*i.e.*, direct reduced iron, or DRI), and various producers are working to develop this option further (Gielen *et. al.*, 2020; HYBRIT, 2016; GrInHy2.0, 2019). The second is the application of CO_2 capture and storage to processes that rely on coal and coke (European Commission, 2016). However, project costs have turned out to be higher than anticipated, and development has stalled.

In addition, biomass products can substitute for coal and coke. For instance, in Brazil, small-scale blast furnaces that use charcoal for iron production are being deployed on a significant scale, with biomass being co-processed in coke ovens. Another option is for the steel industry to relocate electric arc furnaces to areas with ample, low-cost renewable electricity. The sector has already begun building new facilities where inexpensive renewable electricity is available in abundance, such as the Nucor and EVRAZ plants in the United States that will be powered mostly by wind and solar PV.

ALUMINIUM

Aluminium production has the highest energy demand of any non-ferrous metal. The production of aluminium accounts for around 0.8% of global greenhouse gas emissions, and it is the largest electricity-consuming portion of the manufacturing industry, accounting for more than 800 TWh of electricity use in 2015. Fossil fuels are consumed for alumina production, while most of the energy used in the aluminium industry is in the form of electricity used for smelting. The smelting of aluminium is a very energy-intensive process, and over 80% of smelting greenhouse gas emissions are indirect (electricity-related) emissions. The remaining emissions come from direct (on-site) emissions plus the emissions associated with the production of alumina.

In the Transforming Energy Scenario, aluminium production grows from 167 Mt per year in 2015 to 269 Mt per year in 2050; however, CO_2 emissions decline by more than 70% compared to the Planned Energy Scenario in 2050. Much of the reduction is the result of a power system with 86% renewable electricity, but reductions are also achieved from reduced anode use, since less primary aluminium is produced (after accounting for the increase in direct CO_2 emissions from switching to recycled aluminium production). The remainder of the reduction is from energy efficiency measures (including gains from novel smelting technologies) and biofuels use in alumina plants. A key step would be to continue locating plants to areas with available renewable electricity as the share of renewables increases in power generation.

The sector could potentially have the highest use of renewables among all industry sectors, with the share of renewables jumping to 60% by 2050 under the Transforming Energy Scenario. This is an outcome of significant electricity use in production processes coupled with renewable power. In addition, the share of recycled aluminium production would reach half of all production. One option for the industry is to relocate smelting to areas with ample, low-cost renewable electricity. The aluminium sector has already begun building new facilities where inexpensive renewable electricity is available in abundance, such as in Iceland.

A number of emerging technologies already exist to reduce the electricity needed for smelting, while biofuels can easily replace fossil fuels in low- and medium-temperature alumina production. The challenge is to accelerate the adoption of these new approaches, especially in this subset of the industry sector where energy costs play a large role in business decisions. In addition, aluminium smelters can act as virtual batteries for the integration of variable renewable energy (Amelang, 2017). They can operate with surplus renewable electricity, thereby increasing flexibility to power systems and further increasing the viability of siting smelters in areas with an ample supply of VRE sources.

5.7 Challenging sectors: Natural gas infrastructure

Some argue that natural gas is an appropriate fuel for the energy transition due to its lower carbon emissions compared to other fossil fuels, and its use is growing worldwide. However, while natural gas does have lower carbon intensity than other fossil fuels, it is not a zero-carbon solution. The carbon intensity of natural gas use also can vary greatly based on whether the gas is consumed locally via a pipeline, or converted to LNG and transported long distances. For instance, the life-cycle carbon intensity of natural gas exported from the United States to Europe or Asia for use in power generation can add almost 30% to the carbon intensity of the fuel, when all steps are considered, from liquefaction, to transport, to regasification and conversion (Traywick *et. al.*, 2020). Additionally, methane leakage during production and distribution can be substantial, further increasing the associated warming effect attributed to natural gas (Alvarez *et. al.*, 2018).

In the context of policy objectives of "zero" or "net-zero" emission energy systems, projects that are now under construction or planned in the natural gas industry are not consistent with these goals. This raises questions about the future use of gas infrastructure and the risks associated with investments in the natural gas supply – that is, stranded assets and high costs to decommission gas infrastructure. The reuse of the gas infrastructure for green gas, such as carbon-free hydrogen and biomethane, thus offers a strategy for helping to avoid stranding assets while also accelerating greenhouse gas mitigation.

Gas systems can be greened using a combination of upgraded biogas, synthetic methane produced from green hydrogen and CO_2, as well as direct green hydrogen injection into the grid. All three options present interesting emerging opportunities for the use of gas infrastructure, which can help minimise asset stranding, as well as create opportunities for accelerated deployment of renewable energy.

The global biogas supply in 2015 was 1.5 EJ, which represents under 0.5% of total global energy. However, the global potential of biogas could reach more than 35 EJ (IRENA, forthcoming d), which could meet around 30% of natural gas demand. In the Transforming Energy Scenario, biogas supply would increase to 14.4 EJ by 2050 – ten times today's level.

The production of hydrogen or synthetic methane from renewables is technically feasible, although currently costly. In the longer term, cost reductions for electrolysers and the continually falling costs of renewable electricity will improve the economics of hydrogen from renewable sources in the coming decade. The transport of hydrogen via existing and refurbished gas pipelines is currently being explored, with the upgrading of pipelines required when concentrations of hydrogen start to exceed around 20% of the total gas.

Using more hydrogen might reduce new infrastructure investment needs and help to accelerate a transition, but it would also mean that equipment standards would need to be adjusted, which may take time. This potential for switching to hydrogen should not be used as a justification to build new pipelines for "brown gas" now, with the excuse of replacing it with "green gas" in the future. Gas and hydrogen should become greener as soon as possible to avoid any additional contribution to emissions.

06

TOWARDS THE TRANSFORMATIVE DECARBONISATION OF SOCIETIES

6.1 A transformative transition

As countries around the world grapple with the challenge of transforming an energy system – and by extension a global economy – that relies on polluting conventional energy resources, notions of a "Green New Deal" are receiving growing attention. Both the name and the underlying intent are inspired by the massive mobilisation of resources and institutional capacity that took place under the New Deal launched by U.S. President Franklin Delano Roosevelt in the 1930s. The original New Deal entailed fiscal, monetary and banking reforms; public works; and a series of regulatory measures adopted in response to the devastating global financial crisis known as the Great Depression.

In the aftermath of another financial crisis, the Great Recession of 2008, Roosevelt's idea was revived in form of a global Green New Deal. Scholars and international institutions such as the United Nations Environment Programme called for the new scheme to incorporate the climate change dimension (Simms et al., 2008; UNEP, 2009), amid growing acknowledgment of the close interconnections between socio-economic and environmental dynamics.

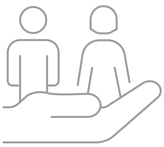
Today, the confluence of concerns over social justice, economic inequality, and rapidly mounting climate threats is driving renewed discussions about a global Green New Deal. As illustrated in Figure 6.1, the concept is essentially a comprehensive policy package that aims to bring together the objectives of achieving climate goals; fostering economic development and jobs creation; and guaranteeing social equity and welfare for society as a whole. The energy transition is at the heart of these objectives.

Figure 6.1 The global Green New Deal: At the heart of solutions to achieve social, economic and environmental objectives
The broader objectives of a Green New Deal

Several different approaches to making economies fit for purpose in today's world have been proposed. Despite different circumstances, institutional contexts and geographies, these initiatives share several characteristics:

- **They acknowledge the need for unprecedented action in the face of grave socio-economic and environmental dangers**, calling for the mobilisation of resources on a scale commensurate with the existential crisis.
- **They endorse or imply the need for greater public intervention** as a remedy. This view is in line with the perspective that market-driven approaches alone will not suffice and that strong policy tools are needed to reach targets for reductions in greenhouse gas emissions determined to be scientifically necessary.
- **They emphasise the opportunities for tackling other social issues simultaneously** (such as equity, the sustainable use of resources, and human health), thus producing synergies and greater prosperity for all.
- **They regard justice for workers and communities affected by necessary economic restructuring as an essential priority** of the energy transition – as expressed, for example, in the European Green Deal – so that the carbon neutrality goal by 2050 goes hand in hand with a socially inclusive approach (see Box 6.1).

Whether a given set of policies incorporates the words "Green New Deal" is less important than its recognition of the imperative of a transformative decarbonisation of societies. This far-reaching form of decarbonisation requires a holistic approach to addressing linked economic, social and ecological problems (Asici and Bunul, 2012), and to advancing the energy transition. Many parts of the world are still recovering from the financial crisis that began in 2008, and yet massive financial resources must be mobilised now to combat climate change.



The energy transition is at the heart of achieving climate goals; fostering economic development and job creation; and guaranteeing social equity and welfare for society as a whole.

Box 6.1 THE JUST TRANSITION MECHANISM OF THE EUROPEAN GREEN DEAL

The European Green Deal proposed by the European Commission in December 2019 recognises that climate change and environmental degradation pose an existential threat to the region and the world. The proposal presents a new growth strategy to make the Union's economy resource-efficient and competitive, with the goal of achieving climate neutrality by 2050. The European Green Deal outlines investments and innovations focused on decarbonising the energy sector, making buildings more energy-efficient, increasing cleaner forms of transport, and supporting greater sustainability in industry, among other objectives.

To reach these goals, a European Green Deal Investment Plan is to mobilise at least EUR 1 trillion over a decade. The initiative acknowledges that the energy transition will entail profound economic and social transformations, and that some regions of Europe will be affected differently from others. As part of the plan, the "Just Transition Mechanism" will seek to mobilise at least EUR 100 billion over the period 2021-2027 to support workers and citizens in the regions hit hardest by the transition. The following financing sources have been identified:

- A "Just Transition Fund" with EUR 7.5 billion in fresh EU funds. Matching funds from Member States, the European Regional Development Fund and the European Social Fund Plus will bring funding to EUR 30-50 billion.
- A dedicated "Just Transition Scheme" under InvestEU, with the objective of attracting private investment to support regions in decarbonising, diversifying and strengthening their economies, may mobilise up to EUR 45 billion.
- A "Public Sector Loan Facility" from the European Investment Bank, backed by the EU budget, is to mobilise another EUR 25-30 billion for purposes such as district heating networks and building renovation.

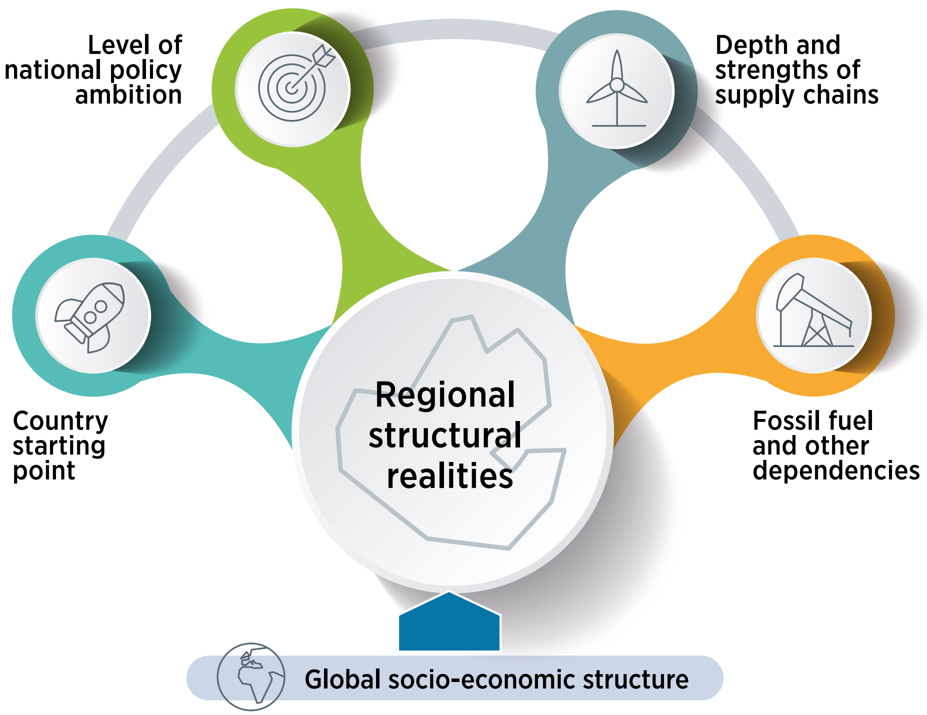
Sources: European Commission, 2019a and 2020.

6.2 Overcoming challenges

Done right, the energy transition not only avoids the use of polluting fuels but creates a vibrant, climate-resilient economy with benefits for all. IRENA's analysis shows that its transition pathway offers strong employment and welfare gains.

Despite positive outcomes at the global level, IRENA's analysis also indicates that the energy transition will generate highly diverse outcomes for regions and countries (see Chapter 4). Individual countries embark on the transition from different starting points defined by their existing socio-economic structures. Their pathways are also strongly influenced by their level of policy ambition. Two sets of conditions influence the ability of countries to derive benefits from the energy transition: (1) the depth, strength and diversity of their national supply chains; and (2) varying degrees of dependency on fossil fuels and other commodities, technologies and trade patterns (see Figure 6.2).

Figure 6.2 Diverse energy transition outcomes for regions and countries
Structural elements that shape the outcomes of the energy transition



Adapted from IRENA, 2020a

Policies devised to drive and support the energy transition and the broader economic transformation must be built on the strengths of individual countries.

As the transition progresses, the differing structural realities in individual countries translate into both challenges and opportunities. Policies devised to drive and support the energy transition and the broader economic transformation must be built on the strengths of individual countries. But they must equally enable them to overcome their structural dependencies so as to take fuller advantage of emerging opportunities. Among these dependencies, three types stand out, namely commodity dependence, technological dependence and trade dependence.

Commodity dependence. Any energy system brings with it a certain dependence on basic commodities (fuels, metals, and other materials) that may be more readily available in some countries than in others. This dependence, which can take a variety of forms, manifests itself not only in the energy sector, but also in the economy at large. The economies of over half the countries of the world, and two-thirds of developing countries, are regarded as commodity-dependent in terms of their export profiles (UNCTAD, 2019).

Beyond export revenues, dependence extends to the many facilities needed for extracting, processing, and selling energy, and has implications for the sectors providing supply-chain inputs, as well as for institutions that educate and train the workforce. However, dependence is hardly limited to sellers. Energy importers, too, have built up extensive infrastructures, distribution networks, assets and human know-how around oil, gas and coal.

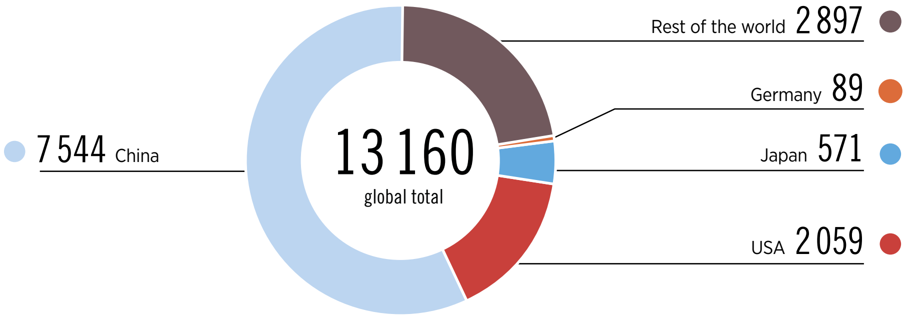
Such forms of dependence may become a liability as the energy transition unfolds. Fossil fuel exporters are expected to face reductions in market demand in the context of growing movements for fossil fuel divestment and decarbonisation (Elgouacem *et al.*, 2020). Both sellers and buyers are increasingly exposed to the risks of stranded assets.

Technological dependence. The capacity to innovate, develop and commercialise technologies is an important indicator of a country's ability to push ahead and take advantage of emerging economic opportunities.

Patent filings are one way to assess countries' technological innovation capabilities. Figure 6.3. shows that during 2018, three quarters of patents pertinent to the renewable energy sector were filed in just four countries. Many countries are unlikely to be able to integrate the high value-added segments of renewable energy value chains and generate associated employment unless, as described in the next section of this chapter, they take urgent steps towards building and leveraging local capabilities.

Cross-economy linkages are typically less pronounced in construction or in operations than in manufacturing, which requires a multitude of components and other inputs from a range of sectors. This is precisely why technological dependence could become an obstacle to unleashing the wider socioeconomic benefits of the energy transition.

Figure 6.3 Renewable energy innovation: Leading countries
Patents filed for renewable energy technologies in 2018



Source: IRENA online patent data platform

The starting point of a country – as expressed in its pre-existing productive capabilities and resource endowment – plays an important role in its ability to develop renewables and other green technologies. Some countries have succeeded in strengthening their capabilities and integrating high value-added segments of renewable energy value chains.

China is an example, given its emergence as the dominant low-cost producer of renewable energy technologies such as photovoltaic cells and modules. The country has pursued a mix of enabling policies (see Figure 6.4) and was able to draw on its well-developed domestic supply chains and manufacturing clusters, as in the Yangtze River Delta (Ball *et al.*, 2017). Similarly, Brazil succeeded in developing a competitive wind turbine manufacturing sector by leveraging pre-existing domestic capabilities in aircraft manufacturing (see Box 6.2).

Box 6.2 LEVERAGING CAPACITIES TO SUPPORT THE ENERGY TRANSITION: THE CASE OF BRAZIL

Innovation scholars argue that catching up with advanced economies involves taking advantage of the window of opportunity temporarily created by technological transitions (Perez and Soete, 1988; Lee, 2013). The energy transition may represent such a chance for developing countries. The key question is how countries can best exploit industrial opportunities presented by the transition and the attendant expansion of global renewable energy value chains.

Pre-existing productive capabilities, particularly in manufacturing sectors with high spillovers to the rest of the economy, appear to play a key role for innovation in green technologies (Anzolin and Lebdioui, forthcoming). In the case of Brazil, Hochstetler (forthcoming) shows that among the key factors behind the success of the wind turbine manufacturing sector was a mix of industrial policies, financial incentives and tax exemptions, and the leveraging of pre-existing domestic capabilities in aircraft manufacturing.

Whether developing countries can acquire the capabilities needed to take advantage of current opportunities in green technology development therefore depends on several factors. Not all countries will necessarily be able to replicate such experiences, and new patterns of dependence could emerge. As noted by the United Nations Economic and Social Council (2019), “for developing countries that lack domestic technological and policy capabilities related to frontier technologies, fulfilling their potential in this regard will require capacity development efforts and related resource support.”

As the energy transition takes hold, new types of dependencies are emerging, not only in renewable energy technologies directly, but also in related fields such as battery storage technologies and materials. At present, the bulk of lithium-ion battery production takes place in a few Asian countries, a situation that is giving rise to efforts elsewhere, such as Europe, to limit this new form of technological dependence (Martín, 2019; European Commission, 2019c).

Trade dependence. As renewable technologies become more affordable, more and more countries undoubtedly benefit from increased access to clean energy. However, the design and manufacturing of the bulk of renewable energy equipment, along with high-value service inputs, still resides in a handful of countries. Many countries, especially those in the developing world, remain consumers rather than producers of technologies such as solar PV panels and wind turbines, limiting associated jobs and other socio-economic benefits deleting to construction, operations and maintenance. These segments of the value chain tend to be low value-added, with limited economic multipliers and fewer cross-linkages to other sectors.

Unless they are able to diversify into higher value-added activities, many countries may not be able to maximise the benefits that arise from the energy and green economy transitions. This presents policy makers with some basic choices, *i.e.*, whether to focus on making renewable energy imports as cheap as possible, or to take steps to nurture local capacities and localise certain inputs along the value chain.

These choices will be contingent on the specific circumstances of each country, notably its market structure and socio-economic outlook. Some countries may find it of interest to build local capacities. In such cases, a logical progression might be to start with domestic assembly of equipment; then to develop specifications and standards that enable locally appropriate equipment designs; and eventually to move into manufacturing certain components or to provide various services linked to renewable energy projects.

Unforeseen developments. The dependencies discussed above are structural in nature and accordingly will require persistent efforts to overcome. The outbreak of the coronavirus and its impact on economic growth and oil demand1 and price, serve as reminders that in a complex world, there are also unforeseen factors that have the potential of disrupting an actual trend or a planned process. It highlights a key contention of this report, namely that the close inter-connections between the energy system and the wider economy are of prime importance.

The close inter-connections between the energy system and the wider economy are of prime importance for a successful energy transition.

[1] The International Energy Agency in revising expectations for demand growth. said global oil demand is set to contract in 2020 - the first full-year decline in more than a decade.

The outbreak of coronavirus will have an impact on the energy transition too, threatening global supply chains in many sectors (Economist, 2020). The oil price volatility can have contradictory effects, such as undermining the viability of unconventional oil and gas resources as well as long-term contracts or lowering fuel costs for motorists, which may encourage more driving and could lessen the appeal of electric vehicles. The severity and duration of the impacts in both cases remain to be seen but will not change the path required to build a low-carbon society.

The bottom line. The foregoing dependencies underscore the need for careful crafting of a series of policy interventions to enable a transition in which no one is left behind. A just and inclusive transition requires a global compact among countries, adequate mobilisation of resources and a tailoring of measures attuned to the challenges faced by various countries.

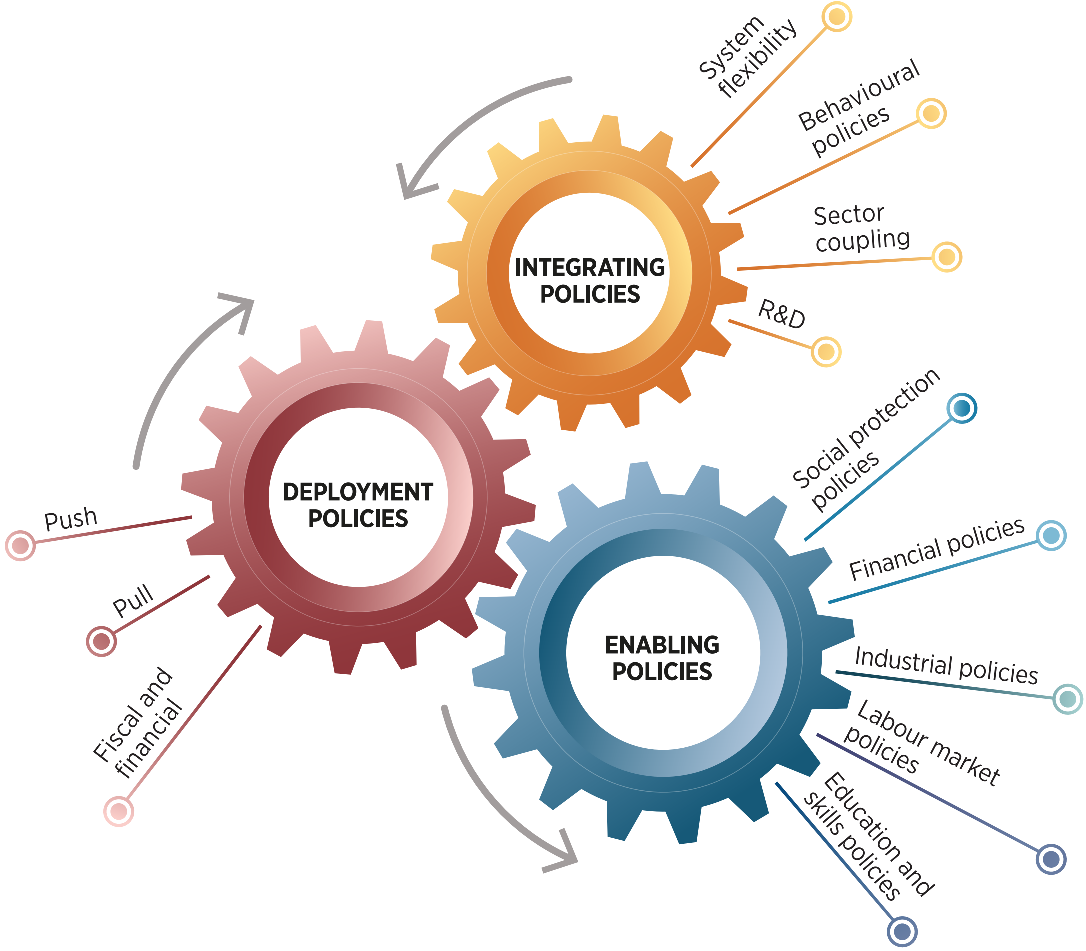
6.3 Policy interventions for a decarbonised society

IRENA's transformation scenarios aim to move the world towards meeting the goals of the Paris Agreement. The Transforming Energy Scenario, if achieved, will result in a 70% reduction in CO_2 emissions by 2050, setting the world on a path toward limiting the rise in the average global temperature to well below 2°C. It is an ambitious goal, yet an achievable one if resources are mobilised and policies initiated at a level commensurate with the challenge.

Ensuring that global temperatures stop climbing will require that early in the second half of this century, net emissions reach zero. Additional mitigation measures will be needed as outlined in IRENA's Deep Decarbonisation Perspective, which highlight the important role of emerging technologies in mitigating CO_2 emissions stemming from energy production, transport, industrial processes and wasteful behaviours.

The energy transition is playing out in the context of intricate interactions of the energy system with the wider economy and the natural environment (IRENA, 2018a). The associated socioeconomic results, analysed at the global level (Chapter 2) and regional level (Chapter 4), provide essential insights for transition planning and policy making. The contours of a policy framework that considers the economic structure and elements for a just transition are illustrated in Figure 6.4. The specifics will vary from country to country, but a comprehensive package will have to include a broad mix of policies and interventions, including deployment and integrating policies and a set of closely connected enabling policies, as described below.

Figure 6.4 A comprehensive package: Deployment, enabling and integrating policies
Policy framework for a just transition



Source: IRENA (2019q)

Co-ordinated **deployment policies** and related measures are required to facilitate the **integration** of renewables into energy distribution systems and end-use applications, and to ensure sufficient system flexibility as variable renewables grow in importance (IRENA, 2019q).

Enabling policies ensure that the energy transition is implemented in ways that are broadly beneficial and that avoid or minimise dislocations for individuals, communities, countries and regions. They include the following:

- Well-designed **industrial policies** that build, enhance, and appropriately leverage domestic economic capacities (IRENA, 2017e, 2017f and 2018d), based on a careful analysis of relevant and transferable material assets and human expertise. Enhancing and leveraging domestic capabilities requires carefully crafted incentives and rules, business-incubation initiatives, supplier-development programmes, support for small and medium enterprises, and promotion of key industry clusters.

- Effective **labour-market interventions** that offer adequate employment services (matching jobs with qualified applicants; promoting employee well-being; facilitating on- and off-job training; and implementing job safety nets), along with measures to facilitate labour mobility, such as relocation grants.
- Targeted **educational and skills development** policies and programmes to take full advantage of the job opportunities that emerge from the energy transition. Co-ordinated by government, strategic collaboration between educational institutions and renewable energy industries can help to reduce or avoid mismatches between skills demand and supply. Special attention is needed to detect opportunities for reorienting the skills and expertise of fossil fuel workers towards the clean energy sector.
- **Social-protection measures** that provide support for vulnerable workers and their communities so that they do not shoulder an unfair burden of the energy transition. This includes measures for income stability through unemployment insurance and other programmes, policy incentives for employers to retain (and retrain) workers where possible, and flexible, longer-term employment contracts to promote job stability.
- Proactive **just-transition** strategies designed to minimise socio-economic disruption. In addition to the policies enumerated above, these may also encompass public investments and economic diversification measures for affected regions and communities.

Many of the measures discussed here involve governmental action. But one of the distinguishing marks of many renewable energy technologies is that their decentralised aspects allow citizens to be more involved and empowered in the energy transition, as recognised by the European Union's new electricity market rules in 2019.[2] Community energy projects can bring about a greater degree of democratisation of energy-related decision making, and thus be an important component of a broader societal transformation spurred by energy transition.

[2] Welcoming the European Parliament's adoption of new proposals for the design of electricity markets, the European Commission commented: *"Through the revised Directive, these new rules will put consumers at the heart of the transition – giving them more choice and greater protection. Consumers will be able to become active players in the market thanks to access to smart meters, price comparison tools, dynamic price contracts and citizens' energy communities. At the same time, energy poor and vulnerable consumers will enjoy better protection"* (European Commission, 2019b).

6.4 Foundations for success: Financial mobilisation, policy cohesion and international co-operation

The global energy transition requires an unprecedented mobilisation of financial resources, driven by the unwavering commitment of governments, the private sector and civil society. Governments must adopt a wide array of policies to strengthen public resolve and ensure that no one is left behind. As the massive financial resources mobilised to counter the 2008 economic crisis demonstrated, countries and societies are collectively capable of such ambitious undertakings. The uncharted territory of COVID-19 and its aftermath presents now another test of our shared resolve for a better future.

Financial mobilisation underpinning energy transitions around the world will require far larger sustained investment in clean energy solutions, including renewable energy and related technologies, such as efficiency, storage and on- or off-grid electrification. Energy investments must occur in tandem with ample funds to minimise social dislocation. Along with ensuring access to clean energy for every individual and community, adjustments must be made to ensure a smooth transition. These include diversifying and revitalising local and regional economies; introducing measures to retrain workers and impart new skills; and offering social-protection programmes.

Strengthening institutions and policy cohesion will be essential. At the national level, robust institutions and dedicated energy transition policies are decisive in driving change at the required scale and pace. Energy ministries have a crucial role in setting out policies and enabling frameworks, but cohesion across sectors and agencies is essential to achieve a broad economic and industrial transformation. Success will depend on collaboration among a broad range of stakeholders.

International co-operation is equally important, not least because of tremendous variations in the ability of individual countries to marshal necessary resources, increase institutional capacities and develop technical know-how. A shared willingness to draw on lessons learned and best practices can herald a strengthened multilateralism for decarbonisation. Such international co-operation must address the needs of countries at varying stages of their energy transitions, ranging from some being committed to carbon neutrality or 100% renewables, to others still at the early stages of tapping their renewable energy resources.

At the same time, international co-operation must be creative enough to overcome challenges and help to accelerate the global learning curve. It must be agile enough to respond to unexpected developments and disruptions during the long-term undertaking to build decarbonised societies and economies.

IRENA, encompassing 160 member countries and over 20 states in accession in early 2020, provides a valuable avenue for co-operation. Its robust and timely knowledge base and comprehensive range of platforms, partnerships and tools, reflects continuous, active engagement on energy transitions worldwide. Established in 2011, the intergovernmental agency works with governments, key global and regional organisations and the private sector to bring about a sustainable and equitable energy future.

The recently formed Climate Investment Platform (CIP) provides a prime example of international co-operation to advance clean energy. Announced at the UN Secretary General's Climate Action Summit in September 2019, it is led by the United Nations Development Programme (UNDP), Sustainable Energy for All (SEforALL) and IRENA in co-operation with the Green Climate Fund (GCF). Working with all interested partners, the CIP aims to mobilise investments in alignment with climate objectives, with an initial focus on regional and national energy transitions. To promote targeted action on the ground, IRENA is co-ordinating the development of sub-regional operational frameworks for CIP implementation. As part of this effort, IRENA will convene regular investment forums at the regional level to support decision makers in creating enabling conditions, assist developers in preparing bankable projects, and improve access to finance.[2]

Ultimately, advancing the global energy transition will depend on the policies that are adopted, the speed at which they are deployed and the level of resources committed. In our interconnected world, international co-operation and solidarity are not only desirable; they are a vital condition to address climate change, economic inequality, and social injustice.

Moving forward, therefore, every investment decision should be based on its potential to accelerate the structural shift towards inclusive, low carbon economies. Anything short of this can severely obstruct the paths to be followed for a transformative decarbonisation of societies.

Moving forward, all investment decisions should be assessed on the basis of their potential to dramatically accelerate the structural shift towards an inclusive low-carbon economy.

[2] To learn more, see: https://irena.org/irenaforcip.

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ABBREVIATIONS

°C	degrees Celsius
bcm	billion cubic metres
BES	Baseline Energy Scenario
bln	billion
CCS	carbon capture and storage
CCUS	carbon capture, utilisation and storage
CDR	carbon dioxide removal
CHP	combined heat and power
CIP	Climate Investment Platform
CO_2	carbon dioxide
CSP	concentrating solar power
DDP	Deeper Decarbonisation Perspective
DH	district heat
DRI	direct reduced iron
EJ	exajoule
EU	European Union
EUR	Euro
EV	electric vehicle
FCEV	fuel cell electric vehicle
G20	Group of Twenty
GCF	Green Climate Fund
GDP	gross domestic product
GJ	gigajoule
Gt	gigatonne
GW	gigawatt
GWEC	Global Wind Energy Council
GWh	gigawatt-hour
H_2	Hydrogen
IEA	International Energy Agency
IMF	International Monetary Fund
IMO	International Maritime Organization
IRENA	International Renewable Energy Agency
kg	kilogram
kWh	kilowatt-hour
LCOE	levelised cost of electricity
LNG	liquefied natural gas
LULUCF	land use, land-use change and forestry
m^2	square metre
MENA	Middle East and North Africa
mln	million
Mt	megatonne
Mtce	megatonne of coal equivalent
Mtoe	million tonnes of oil equivalent
MW	megawatt
MWh	megawatt-hour
N_2O	nitrous oxide
NDC	Nationally Determined Contribution
O&M	operation and maintenance
OECD	Organisation for Economic Co-operation and Development
PES	Planned Energy Scenario
PPA	power purchase agreement
ppt	percentage point
PV	photovoltaic
R&D	research and development
RE	renewable energy
REmap	renewable energy roadmap analysis by IRENA
SDG	Sustainable Development Goal
SEforALL	Sustainable Energy for All
SF6	sulphur heaxfluoride
t	tonne
TES	Transforming Energy Scenario
TFEC	total final energy consumption
TJ	terajoule
toe	tonne of oil equivalent
TPES	total primary energy supply
TW	terawatt
TWh	terawatt-hour
UK	United Kingdom
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
USD	US dollar
VRE	variable renewable energy
WHO	World Health Organization
yr	year

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