circular carbon economy

02

Reduce: Non-bio renewables.

IRENA
International Renewable Energy Agency

International Renewable Energy Agency

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Abbreviations

BES	Baseline Energy Scenario
CCS	carbon capture and storage
CCU	carbon capture and utilisation
CDR	carbon dioxide removal
CHP	combined heat and power
CO_2	carbon dioxide
DDP	Deeper Decarbonisation Perspective
EJ	exajoule
EU	European Union
EVs	electric vehicles
FiTs	Feed-in tariffs
G20	Group of Twenty
GDP	gross domestic product
GHG	greenhouse gas
Gt	gigaton
IEA	International Energy Agency
IPCC	Intergovernmental Panel for Climate Change
IRENA	International Renewable Energy Agency
KAPSARC	King Abdullah Petroleum Studies and Research Centre
LCOE	levelised cost of electricity

Abbreviations

MW	megawatt
NDCs	nationally determined contributions
PES	Planned Energy Scenario
PV	photovoltaic
R&D	research and development
SDG	sustainable development goal
TES	Transforming Energy Scenario
TFEC	total final energy consumption
TPES	total primary energy supply
TSO	transmission system operator
USD	United States dollar
VRE	variable renewable energy

Executive Summary

The health, humanitarian, social and economic crises set off by the COVID-19 pandemic have been unprecedented with wide-ranging impacts on societies around the world and thus require a decisive, large-scale response guided by appropriate social and economic measures. However, as countries consider their economic stimulus options, they should not lose sight of the need to meet the global climate and sustainability objectives through the decarbonisation of our societies.

Renewable energy solutions provide clean, reliable, cost-effective and easy-to-mobilise energy for different services, including essential ones, such as healthcare, water and food supply. These characteristics make renewable energy technologies decisive in the immediate response to COVID-19. While also reducing global climate-changing emissions, renewable energy technologies could play a key role in the economic recovery from the pandemic, ensuring sustainability and energy security, creating jobs and strengthening resilience to protect and improve people's health and welfare.

Renewable energy technologies lie at the heart of the energy transition and are key for the creation of energy systems that guarantee a secure and affordable energy supply for all people, and at the same time protect the environment and the climate. IRENA's analysis shows that the swift adoption of renewable energy solutions combined with energy efficiency strategies constitute safe, reliable and affordable pathways capable of achieving over 90% of the energy-related carbon dioxide (CO_2) emissions reductions required to meet nationally pledged climate goals.

Currently, renewable technologies are already dominating the global market for new power generation capacity. Solar PV and wind are increasingly cost-competitive and affordable sources of electricity in many markets, and most renewable power sources will be fully cost competitive within the next decade. Renewable power generation is now growing faster than overall power demand and many innovative solutions are currently being developed to make the power system and grids more flexible, allowing for higher and more cost-effective use and penetration of renewables. Distributed energy resources, such as rooftop solar PV, behind-the-meter batteries and electric vehicles (EVs), are emerging as promising solutions for improved resource efficiency, increased flexibility and better planning by grid operators. The variability of renewable energy generation can be overcome with key enabling technologies, such as utility-scale battery solutions, heat pumps and smart grids, all of which are experiencing rapid growth and reductions in costs.

Indeed, a power system dominated by renewables can be a reality, and the scale and speed of renewable energy deployment can be accelerated with confidence. The share of renewable energy (including biomass) in the power sector would increase from 25% in 2017 to 86% by 2050, mostly through growth in solar and wind power generation. Solar and wind power are already procured at prices competitive with other sources of electricity as a result of technological improvements and supportive policies, and such measures will continue to be needed. This transformation would require new approaches to power system planning, business models, market design and systems operation to achieve the system flexibility needed. On a technology level, a crucial role will be played by long-term and short-term storage, grid expansion, interconnections, smart grids, demand-side management and sector coupling (i.e. EVs and heat pumps).

Industry, transport and the buildings sectors will need to use more renewable energy. In these sectors, the most important synergy of the global energy transformation comes from the combination of increasing low-cost renewable power technologies and the wider adoption of electric technologies for end-use applications in transport and heat (sector coupling). Electrification of end-use sectors would lead the transition and additional measures will be required to enable the electrification of all end uses with renewables-based power (or "Green" electrification). However, support should also be given to renewable energy in the "hard-to-abate" sectors, such as heavy industry (i.e. cement, chemicals and petrochemicals, and iron and steel) and heavy transport (i.e. aviation, shipping). Solutions for these sectors include both direct uses of electricity, as well as energy carriers such as green hydrogen and synthetic fuels, which are also emerging as potential game changers. In the transport sector, biofuels deserve more attention; this is dealt with in a separate report.

The transition towards a decarbonised global energy system will require a change in types of investments, with a shift in the composition of investments away from the fossil fuel sector towards renewables, enabling infrastructure and energy efficiency. Cumulative investments in the energy system over the period to 2050, including infrastructure and efficiency, would reach USD 110 trillion. Of that total, over 80% needs to be invested in renewables, energy efficiency, end-use electrification and power grids and flexibility.

These investments have the potential to bring significant socio-economic benefits. First, the investments would stimulate considerable job growth, most of this directly in renewables, where employment would rise to 42 million jobs by 2050. Second, the global GDP would grow and generate USD 98 trillion of cumulative gains, largely due to changes in consumer spending in response to fiscal policy, as well as other indirect and induced factors. Finally, welfare, which measures the quality of life in terms of economic, social and environmental aspects, would also improve faster and further.

Despite the powerful factors driving the global uptake of renewable energy, multiple barriers inhibit further development in developed and developing countries. These vary based on specific markets and renewable energy technologies. They span from finance and cost challenges to barriers related to awareness and culture.

However, as countries and regions embark on their transformation pathways, the successful energy transition will depend on several policy interventions. Governments need to assert their commitments towards the energy transition through ambitious targets in order to drive markets and innovation. In addition to measures to support deployment and technological innovation (i.e. pricing and competitive procurement, capital grants), further enabling policies include targeted public investments in enabling infrastructure, industrial policies (i.e. to support the development of domestic renewables industries), labour market and educational and skills development policies, and social protection measures to ensure equal distribution of transformation impacts (i.e. targeting women and marginalised communities). 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 cooperation and solidarity are not only desirable, they are vital for addressing climate change, economic inequality and social injustice.

G20 member states share a strong economic and political interdependence, which creates a common interest in combining efforts to create a sustainable and stable global environment, including addressing the global energy situation and the climate crisis. In light of the changes needed for the energy transformation to happen, this report argues that G20 countries as a group can play a key role in fostering the development, deployment and spread of renewable energy technologies.
The energy transition will succeed in fighting climate change only if the right policies are in place in a timely fashion. The G20 framework for action should take into account the deployment of renewables through actions that make energy a catalyst of economic, inclusive and sustainable growth. Targets, supporting policies, capacity building, and products and services innovation are at the center of the engagement needed from policy makers.

G20 Recommendations

Renewable energy technologies lie at the heart of the energy transition and are already dominating the energy global market. However, accelerating the energy transition requires concentrated action across multiple elements of an enabling environment. Strengthening institutions and policy cohesion within countries will be essential.

At the national level, robust institutions, national champions and citizen participation can play key roles in accelerating the energy transition and driving change at the scale and magnitude needed. Energy ministries are important actors in setting policies and enabling frameworks; however, policy cohesion among ministries and agencies is essential to advance broad economic and industrial transformation. At an international level, cooperation is also important, as countries have different ways of managing resources, raising institutional capacities or developing technical know-how. As such, sharing national expertise helps countries to draw on lessons learned and best practices, as well as fostering a strengthened multilateralism for decarbonisation. International cooperation must address the needs of countries at different stages of the energy transition, ranging from those that have committed to carbon neutrality or 100% renewables to others which are still at the early stages of tapping their renewable energy resources. At the same time, international cooperation must be creative: Innovative tools and forms of collaboration must be developed to overcome the new and unique challenges of achieving a decarbonised society and economy.

The strong economic and political interdependence shared by all G20 members creates a common interest in combining efforts to create a sustainable and stable global environment, which indeed also applies to the world's energy, climate and environmental situation. As explored in this report, G20 countries as a group can foster the changes needed for renewable energy development and spread such change on a global level. The G20 framework for action depends on a policy framework that takes into account the deployment of renewables through actions that make energy a catalyst of economic, inclusive and sustainable growth. The following five topics aim to frame and highlight decisive actions and measures: i.) target setting; ii) policy, regulation and social protection measures; iii) scaling up investment for the energy transition; iv) resources and capacity building; and v) products and services innovation.

Topic 1: Target setting

Status and challenges:

Five years after the Paris Agreement, countries around the world are struggling to translate their pledges into concrete targets and actions to fight climate change. National targets have so far focused on the power sector, neglecting renewable energy opportunities in end uses. In addition, in many countries, renewable energy targets set in NDCs are not aligned with national energy strategies, sending inconsistent signals to investors.

Recommendation:

Establish long-term energy planning strategies and define consistent and transparent national targets encompassing the energy sector as a whole.

Actions:

- **Increase ambitions** in national pledges to scale up renewables and cut CO_2 emissions.
- **Align renewable energy targets** in NDCs with national energy strategies and plans to provide clear and strong signals to investors.
- **Broaden the scope of renewable energy targets** to encompass the whole energy sector and to **enhance their transparency.**
- **Develop targets as part of long-term energy scenarios** to support the planning for a climate-friendly energy system and expanding the planning beyond the power sector.
- **Periodically assess and revisit targets** to make sure that they are in line with the country's status and adjust them depending on the progress and other factors.
- **Facilitate a broader participation and stronger coordination** across different stakeholders.
- **Translate the planning in concrete actions** to promote a faster energy transition.

Topic 2: Policy, regulation and social protection measures

Status and challenges:

As more and more variable renewable energy (VRE) is deployed in power systems, flexible resources are beginning to be deployed, with innovative measures taken to adapt the power systems. Despite the remarkable progress made in the power sector, the heating and cooling and transport sectors are lagging behind in their paths toward decarbonisation and require immediate policy attention. In addition, policy makers will have to make sure the energy transition is a just one, leaving no one behind.

Recommendation:

Continuously adapt policy instruments to integrate higher shares of renewable energy into the energy system, increase the deployment of renewables in end uses and achieve broader socio-economic objectives.

Actions:

- **Adopt policy support schemes that address some of the challenges related to VRE system integration,** switching from a cost-only approach to a value-based one.
- **Invest now in flexible resources** (storage, demand side management, smart grids, etc.) innovation and deployment.
- **Introduce, in both regulated and liberalised power systems, a market design fit for the renewable era** that is able to provide stable and long-term signals that reward renewable generation and provide economic incentives for the flexible resources.
- **Adopt plans and measures to deploy green electrification** in the transport and heating sectors in a timely fashion, to unlock the synergies between increased electrification and VRE.

- **Introduce or increase the policy support to the direct use of renewables** in the heating and cooling and transport sectors, with mandates, incentives and fiscal and behavioural policies to support the decarbonisation of all end uses.
- **Fund RD&D** to support the development of solutions to decarbonise "hard-to-abate" sectors.
- **Pursue social objectives within the energy transition,** in addition to procuring renewable energy cost-effectively.

Topic 3: Scaling up investment for the energy transition

Status and challenges:

Despite steady growth over the past decade, global annual investments in renewables need to more than double (or almost triple) compared to current levels to achieve a global energy transition in line with international climate and development objectives. The COVID-19 crisis has added strains on the global financial system, curtailing finance flows to renewables in the first five months of 2020, compared to the same period in 2019.

Recommendation:

Use public finance strategically to mobilise all available sources of private capital, especially large institutional investors, and secure long-term commitments to lower carbon alternatives, including renewables.

Actions:

- **Public finance from governments and Development Financial Institutions (DFIs) should shift away from fossil fuels** and be directed towards green infrastructure assets, such as renewables.
- At a time when governments' economic and fiscal responses to the COVID-19 pandemic have strained public resources, **public finance should be used strategically with a focus on attracting additional private capital**.
- **Risk mitigation instruments can be used to effectively to lower risks and barriers for investors, while at the same time reducing public capital requirements**.
- Public finance should be used in a targeted manner to **reduce technology costs and spur investments in hard-to-enter sectors and markets** (e.g. off-grid renewables in rural areas), as well as to **support demonstrations and first-of-a kind commercial scale processes** for clean energy carrier production and industrial processes.
- **Public finance could focus on climate-smart infrastructure and technologies to achieve higher penetration of renewable energy as well as on deeper electrification of end-use sectors**.
- **Policy makers and regulators can stimulate greater institutional investors' participation in renewables** by setting supportive policy and regulatory frameworks and lowering specific barriers faced by these investors.

- **Policy makers and public financial institutions can support the supply of green bond issuances for renewables and strengthen their credibility among market participants** by adopting green bonds standards, reviewing institutional investors' mandates for green assets (including renewables), providing technical assistance and economic incentives, and creating pipelines of bankable renewable energy projects.

Topic 4: Resources and capacity building

Status and challenges:

Currently, more progress can be made in the development of educational programmes and specialised vocational training that would fully exploit the potential for job creation in renewable energy and energy efficiency. Capacity building is a central pillar of an enabling environment for decentralised renewable energy development, and the presence of adequate skills is key for the sustainability of the decentralised renewable energy sector.

Recommendation:

Promote networks to facilitate and invest in capacity building and education.

Actions:

- **Create targeted educational and skills development policies** and programmes to take full advantage of the job opportunities that emerge from the energy transition.
- **Offer technical education and training** at dedicated institutions or as part of university curricula, both online and onsite, to help equip the workforce with adequate skills and increase opportunities for local employment.
- **Introduce skills and educational programs** at universities and as short-term and certificate courses, as well as specialised training.
- **Facilitate reskilling the work force and reorienting it** from the fossil fuel industry and other industries to renewables.

Recommendation:

Enhance and leverage domestic capabilities to motivate and engage people in sector development.

Actions:

- **Promote business incubation initiatives** and support for small and medium enterprises.
- **Promote renewables-based research and development strategies,** as well as institutions to advance the uptake of R&D results in the public and private sectors.
- **Encourage university-industry cooperation on renewables,** through public research and labour mobility for scientists and researchers.
- **Incentivise supply chain participation in renewable sectors** by local firms and actively support the creation of partnerships.

Topic 5: Products and service innovation

Status and challenges:

The existing renewable energy solutions still have a large and unexplored potential to innovate and to allow any customer from cities, islands or rural areas, regardless of expertise, to independently use the application. Therefore, technology adaptation, innovation and improvements – in generation, balance-of-system components and end-use applications – are essential for the success of renewable energy solutions.

Recommendation:

Encourage innovations in renewable energy products and services while facilitating technology accessibility.

Actions:

- **Adopt a systemic approach,** drawing together innovations in enabling technologies, market design, business models and system operation.
- **Improve existing infrastructure** along with building high-voltage grids or supergrids.
- **Facilitate competitive environments** in which reductions in the cost of energy are both rewarded and supported through the provision of targeted public R&D funding.
- **Design policies promoting energy transformation planning** as part of a wider infrastructure development, thereby integrating renewables as a core strategy of infrastructure expansion.

Further Actions for IRENA

IRENA is a key global actor at the heart of the global dialogue on energy and has a special commitment and remit to the development of a renewables-based energy transition. Thanks to its global membership, IRENA has a unique convening power and can support G20 members in addressing the above recommendations and making full use of the potential of renewables. In particular, G20 countries should mandate and support IRENA to:

- **Mainstream the use of renewables as part of long-term energy scenarios planning.** As part of IRENA's work with member countries on energy system roadmaps and plans, IRENA can assist countries in fully exploring their renewables potential.
- **Develop and share evidence to inform strategies.** IRENA's work aims to gather and share knowledge on the latest state-of-the-heart renewable energy technologies. This includes renewable energy costs developments, mapping of innovations and annual reviews of renewable energy employment, as well as analysis of policies and benefits.
- **Convene diverse groups of stakeholders for knowledge sharing and joint strategy development.** IRENA's global membership can bring together disparate policymakers, as well as a diversity of stakeholders, such as other international organisations, private sector actors and industry players and non-governmental organisations.
- **Provide energy project development tools** to assist in the development of bankable renewable energy projects, and act as a facilitator connecting project owners, financiers/investors and technology suppliers to bring projects to fruition.

01

Introduction

Introduction

Climate change has become one of the greatest threats of this century to environmental, as well as global, security, with adverse impacts on health, wealth and political stability. Over the past decade, energy-related CO_2 emissions have increased by 1% per year on average, despite levelling off periodically. If historical trends continue, energy-related emissions will 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. Governments' current and planned policies would result in a levelling of emissions, with emissions in 2050 similar to those today, but this would still cause a temperature rise of about 2.5°C. The Paris Agreement establishes a goal to limit the increase of global temperature to "well below" 2°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.

The importance of an energy transition is explored by the King Abdullah Petroleum Studies and Research Centre (KAPSARC) through the concept of a "circular carbon economy". Under this approach, all climate mitigation options are included and can be linked together in a system that achieves the climate goals laid out in the Paris Agreement. The key principle for carbon management is the "three Rs" of reduce, reuse and recycle, and adding a fourth R for "remove". The current paper focuses on "reduce", which in Saudi Arabia's circular carbon economy represents all of the carbon mitigation options that reduce the amount of carbon entering the system. Those options are energy efficiency (both on the supply and demand side), non-biomass renewables and nuclear power.

Energy systems around the world are undergoing radical changes, driven by a combination of technological innovations, the need to expand affordable energy access and the urgent need to tackle climate change. This global energy transformation can pave the way for a more inclusive, secure, cost-effective and sustainable future, with the current energy mix, dominated by fossil fuels, making way for clean, abundant renewable energy. Due to its declining costs and compelling business case, renewable energy has established itself as the technology of choice for new power generation capacity and is a key driver of the global energy transformation. Solar PV, onshore wind and hydropower can all now provide electricity competitively compared to fossil fuel-fired power generation. Renewable energy technologies also contribute to energy security, as they almost exclusively use local resources and insulate economies from external shocks. They are also one of the fastest ways to expand access to electricity through distributed energy systems. Countries taking full advantage of their renewable energy potential will realise a host of socio-economic benefits, such as increased job creation, reduction of local air pollution, and significantly improved health and welfare.

Renewable energy deployment needs to grow faster than current trends to achieve global climate objectives and Sustainable Development Goals. However, there are technically feasible and economically attractive solutions to increase this growth. Indeed, there is a unique opportunity to accelerate the transformation towards digitalised, distributed and decarbonised energy systems, and there are already many innovations available for enabling technologies, business models and system operation to accommodate large shares of renewable energy.

The crucial role of non-biomass renewable energy in the fight against climate change and reduction of CO_2 emissions is examined through IRENA's energy transformation scenario. This report highlights the central role of renewable energy technologies in the energy transformation. It discusses the potential of renewable energy technologies and the strong business case supporting them, the already available innovations and further opportunities to integrate variable renewable energy into the grids, as well as their positive externalities and socio-economic benefits.

02

Current Status

This section will show how renewable energy is a proven and available technology by providing the latest figures, trends and market developments in renewable energy deployment worldwide. The strong business case for renewables is demonstrated by their cost, performance and deployment evolution, especially when considering trends in solar PV, wind and other renewable power generation options, along with the growing viability of energy storage technologies. The current innovation landscape for enabling technologies, business models and system operation will also be outlined and discussed.

Transformative energy developments

In the last few years, the energy sector been changing in promising ways.

The **costs of renewable energy have continued to decline rapidly**. IRENA's latest report, Renewable Power Generation Costs 2019, shows that the global weighted average cost of electricity from all commercially available renewable power generation technologies continued to fall in 2019 (IRENA, 2020a). For example, the global weighted average levelised cost of electricity (LCOE) from utility-scale solar photovoltaic (PV) projects fell a remarkable 82% between 2010 and 2019, reaching USD 68 per megawatt-hour (MWh), while the cost of electricity from onshore wind declined 39% to USD 53/MWh.

Moreover, new projects are increasingly being commissioned at very low absolute cost levels. In 2019, 56% of all newly commissioned utility-scale renewable power generation capacity provided electricity at a lower cost than the cheapest new fossil fuel-fired option. Nine-tenths of the newly commissioned hydropower capacity in 2019 cost less than the cheapest new fossil fuel-fired option, as did three-quarters of onshore wind capacity and two-fifths of utility-scale solar PV. The latter value is remarkable considering that in 2010, solar PV electricity cost 7.6 times the cheapest fossil fuel-fired option (IRENA, 2020a).

Renewable power generation continues to grow in 2020, despite the COVID-19 pandemic, but new capacity additions in 2020 will be lower than the new record previously anticipated. Nonetheless, renewables steadily increasing competitiveness, along with their modularity, rapid scalability and job creation potential, make them highly attractive as countries and communities evaluate economic stimulus options.

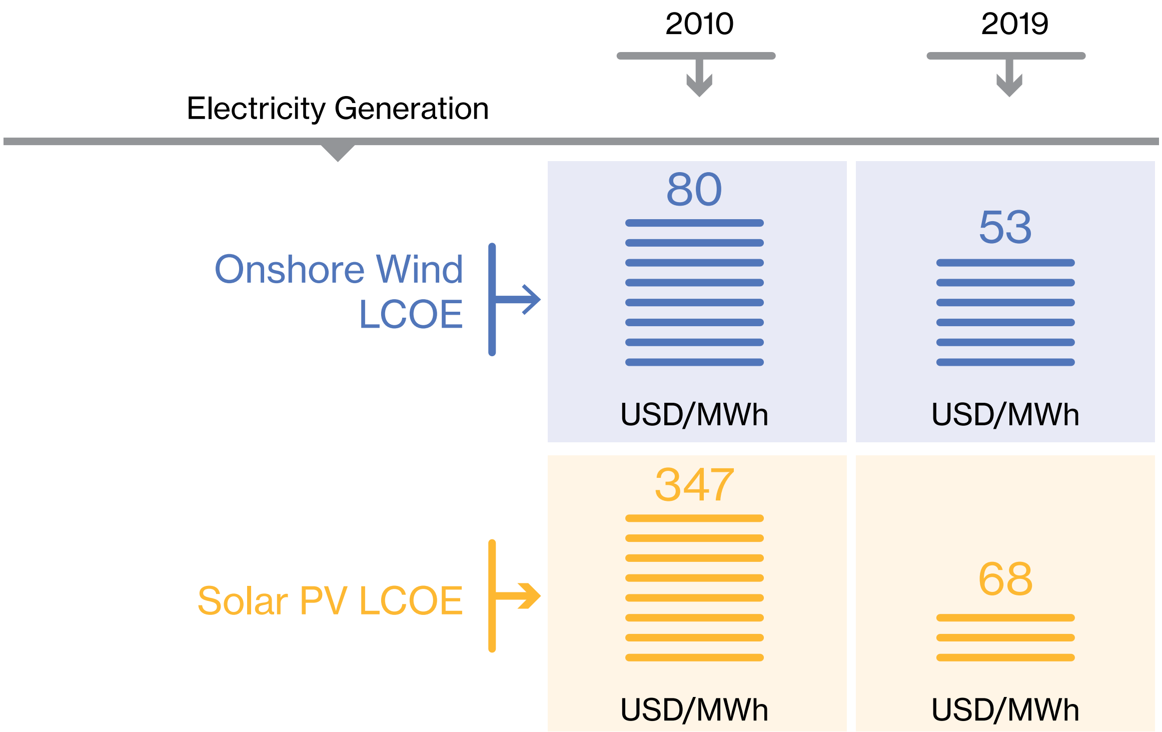


Figure 1. Evolution of LCOE costs for solar PV and wind onshore (2010- 2019)
Source. Data extracted from (IRENA, 2020a, 2020b)

The **share of renewable energy in electricity generation has been increasing steadily in the past years** and renewable power technologies are now dominating the global market for new generation capacity. From 2010 to 2018, the renewable electricity generation share increased from around 20% to nearly 26%, or 18% to 23% without considering bioenergy (IRENA, 2020b). Progress is being seen everywhere. In China, the capacity of wind and solar energy reached 20% of the total installed capacity by the end of 2019 (China Electricity Council, 2020); Chile is undergoing a renewable energy boom and for the last few years has been one of the largest renewables markets in Latin America; and Morocco is progressing as well, with renewable power providing already 35% of its electricity and aiming at achieving 42% by 2020 (Morocco World News, 2020). Wind and solar PV power dominated overall renewable energy additions in the power sector again in 2019, with an estimated 60 gigawatts (GW) of wind power and 93 GW of solar PV power installed (IRENA, 2020b). For the eighth successive year, the net additional power generation capacity of renewable sources exceeded that of non-renewable sources. Global electricity markets are constantly evolving to meet the growing demand for renewable energy required by different types of consumers, including companies. Indeed, more and more companies around the world are actively investing in self-generation and are procuring renewable energy. IRENA estimates that at the end of 2017, the corporate renewable electricity market reached 465 terawatt hours (TWh), representing approximately 3.5% of total electricity demand and 18.5% of renewable electricity demand in the commercial and industrial sectors (IRENA, 2018).

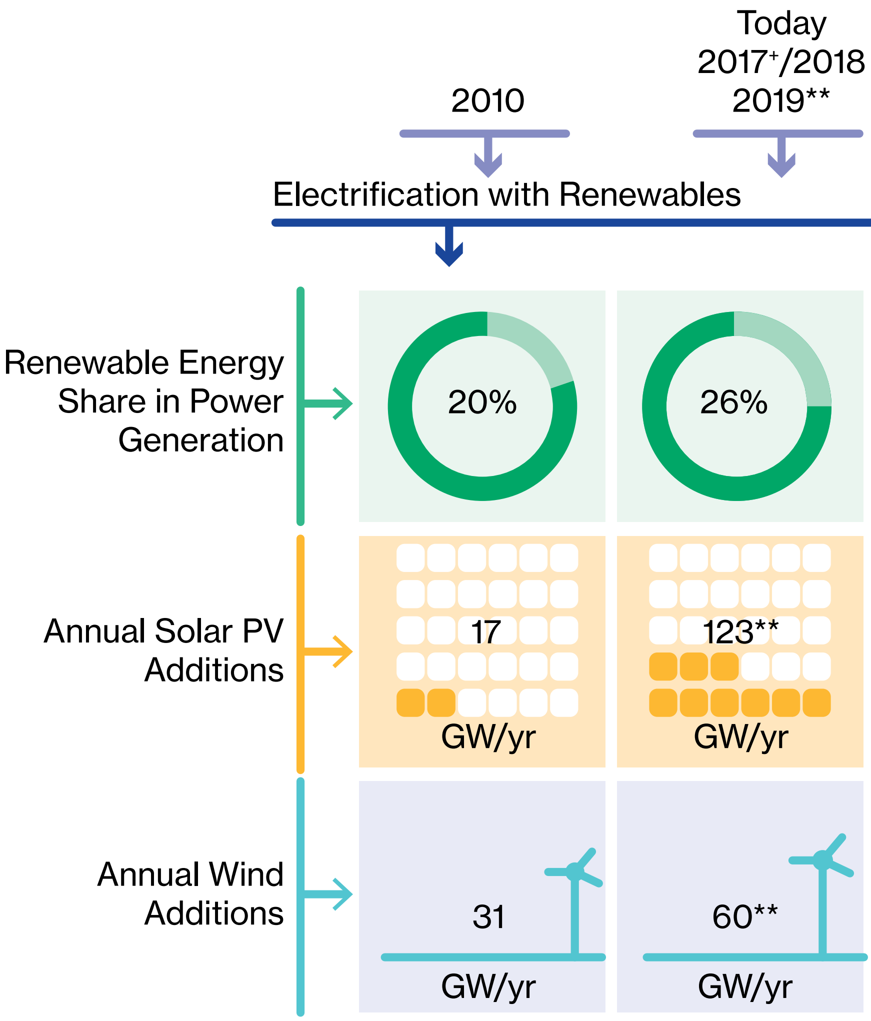


Figure 2. Evolution of renewable energy in the power sector (2010- 2017/2018/2019)
Source. (IRENA, 2020b)

Dramatic shifts are taking place in the way that energy systems operate, driven by increased digitalisation, the decentralisation and democratisation of power generation, and the **growing electrification of end-use sectors**. Indeed, the main driver for the energy transformation is increased use of electricity, such as in the growing electric mobility revolution. Electric vehicle (EV) sales (both battery-electric and plug-in hybrids) reached 2.2 million units in 2019 (InsideEVs, 2020a), continuing the growth from the previous year. In Norway, the total number of EV registrations in 2019 increased 10% more than the previous year and the market share increased to a new record of close to 56%, with more than a half of all passenger cars sold being electric that year (InsideEVs, 2020b). Globally, around 7.9 million passenger electric cars were on the road by the end of 2019 (Der Spiegel, 2020). The switch to electricity is not just happening with cars. Electric buses are making large inroads, particularly in China, where some cities have converted their entire public bus fleets to electricity. For instance, Shenzhen has over 16 000 electric buses in operation. While electricity is clearly making inroads in transport, steps are also being taken to electrify heat. In some Nordic countries, heat pumps now account for more than 90% of the sales of space heating equipment, and countries are starting to explore the use of heat pumps and electric boilers with storage for their district heating systems.

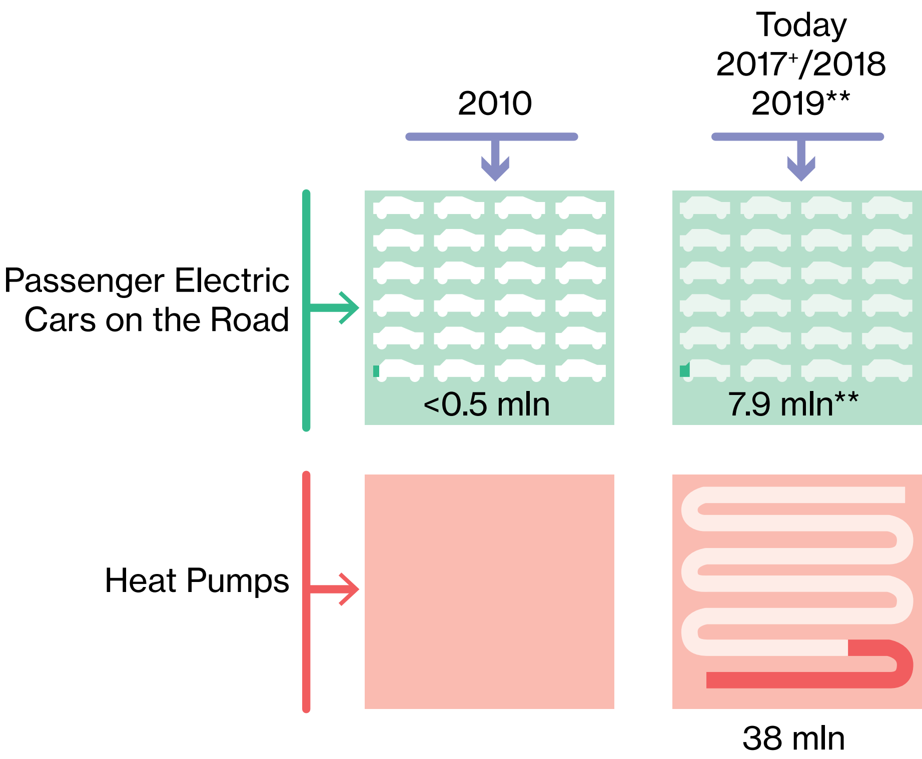


Figure 3. Evolution of electrification of end-use sectors
Source. (IRENA, 2020b)

Strong political commitment to the energy access agenda at the national and global level, combined with financing, local entrepreneurship and technological innovations, have enabled progress in **energy access**. The number of people living without electricity access decreased to 789 million in 2017, with the global electrification rate reaching 90%. Access rates in rural areas – where most of those without access live – have been growing rapidly and now stand at about 80%

(IEA, IRENA, UNSD, World Bank, WHO, 2020). Today, technologies and solutions are available to dramatically accelerate this growth, because technology costs have plummeted, innovation in delivery models and financing has picked up, and a more diverse set of stakeholders, including communities, local entrepreneurs and the private sector, have become engaged in the sector. For example, off-grid renewable energy solutions, including stand-alone systems and mini-grids, have become mainstream, cost-competitive options. By 2018, about 35 million people had access to off-grid sources of electricity (IEA, IRENA, UNSD, World Bank, WHO, 2020). Besides providing electricity services for households, off-grid solutions are also increasingly supporting public services (e.g. education, water and primary health care) and livelihoods (e.g. in agriculture). Off-grid renewable energy options are rapidly scalable and environmentally sustainable and can be tailored to local conditions. Importantly, they have the potential to empower rural communities, especially youth and women (IRENA, 2019a).

Meanwhile, **renewable energy investment** continues to grow. Bloomberg New Energy Finance estimates total investments at USD 363 billion in 2019 (BNEF, 2020). Even oil majors are investing more in the clean electricity business. Royal Dutch Shell recently said it could develop a power business and mentioned that it could become one of the largest electricity companies globally by 2030 (The Guardian, 2020). Similarly, Total is aiming to become a global integrated leader in solar power over the next five years (NS Energy, 2020) and the Italian company ENI recently announced a goal of cutting its carbon footprint 80% by 2050 (ENI, 2020).

Innovations in energy technologies play key roles in facilitating the integration of variable renewable energy (VRE) and a large number of emerging innovations are already being implemented worldwide (IRENA, 2019b).

For instance, **battery storage technologies** (both utility-scale and behind-the-meter) can help cope with the variability of renewables and provide various services to the grid. Battery storage systems can provide grid services such as frequency response, regulation reserves, ramp rate control and black start services (IRENA, 2019b). On a technology level, both long-term and short-term storage are key for increasing system flexibility. Currently, there are 30 gigawatt-hours (GWh) of stationary storage (which excludes EVs) and 200 GWh of storage available to the grid from the EV fleet. This is projected to rise to 9 000 GWh by 2050 (IRENA, 2019b). **Digital technologies,** such as the internet of things, artificial intelligence, big data and blockchain are introducing new applications in the power sector, changing the boundaries and dynamics of the industry and helping to optimise renewables assets. They all contribute to better power sector management through such advances as the forecast of renewable energy generation, the automated control of power plants, the maintenance of grid stability and reliability, and efficient demand-side management (IRENA, 2019c). Recent advances also make it possible for **new and smart grids** (mini-grids and supergrids) to play important roles in the transformation of the global energy system. Besides providing electricity to consumers, renewable smart grids can provide key services to the main grid that enable new ways to manage VRE generation, such as flexibility through electricity imports and exports and integration of distributed energy. They also can provide ancillary services like frequency control, voltage stability and congestion management (IRENA, 2019b). Other **technologies enable the electrification of other sectors,** opening doors to new markets for renewable generation, as well as ways to store the generation surplus. These technologies include electric vehicle smart charging, renewable power-to-heat and renewable power-to-hydrogen (IRENA, 2019b). The emergence and new value offered by these technologies create business cases for new services that enhance the energy system's flexibility and incentivise further integration of renewable energy technologies. **Innovative business models,** such as aggregators, pay-as-you-go and community-ownership models, are emerging and empowering consumers, turning them into active players (IRENA, 2019c). The new technologies and market regulations will also enable **power systems to address new operational challenges,** including: i) coping with the increased share of distributed generation and the decentralisation of the system, which requires new operational practices and cooperation between distribution and transmission system operators; and ii) developing new operations practices to manage the uncertainty of VRE generation.

Table 1 outlines some examples of successful projects using the innovations described above to integrate variable renewable energy in the grid.

Type of innovation	Project name	Country	Service provided	Description
Utility-scale battery	38.4 MW/250 MWh sodium-sulphur battery by Terna	Italy	Grid investment deferral and reduced RE curtailment	Wind curtailments were caused by an excess of wind generation in the south and low transmission capacity to transport energy to the north. In 2015, Terna installed the battery system to store the excess wind energy and use it during later periods with low wind demand, avoiding the need to invest in new transmission capacity. Additionally, storage provides services such as primary and secondary reserves, load balancing and voltage control.
Behind-the-meter battery	Johnson Control International's 100 kW/ 182 kWh BTM energy storage system at its APAC headquarters	Shanghai, China	Demand charge reduction and increased self-consumption	The intended application of the BTM battery is to reduce utility costs through demand charge management along with providing storage for the installed solar PV system and providing charging for EVs.
Artificial intelligence and big data	DeJoule, Smart Joules	India	Demand forecast and demand-side management	DeJoule is an air conditioning optimisation platform with built-in software that uses AI to facilitate demand-side management and enhance the efficiency and performance of air conditioning systems while decreasing costs for consumers.
Vehicle-to-grid	ELBE project	Hamburg, Germany	Smart charging	The project installs EV charging stations in buildings and on commercial premises. The project includes the application of V2G technology and load-dependent tariffs, where EVs are considered as controllable consumption.

Table 1. Examples of innovations integrating variable renewable energy
Source. (IRENA, 2019b, 2019d, 2019e)

The strong business case for VRE technologies such as wind and solar PV has positioned these technologies at the core of the energy transition. Innovations being trailed in front-running countries show that power systems can be operated with very high shares of VRE in a reliable and economical way. For example, in 2019, renewable energy sources accounted for 99% of the power generated in Costa Rica and 98% in Uruguay, with wind power accounting for 17% of the power mix in Costa Rica and 35% in Uruguay (Renewables Now, 2019; RVE, 2019). Moreover, in 2019, the share of VRE in power generation was over 50% in Denmark (47% wind and 3% solar PV), over 40% in Lithuania and 34% in Germany (23% wind and 11% solar PV) (Business day, 2020; RENEWEconomy, 2019). Other records in VRE integration were set in 2019. The German transmission system operator (TSO) was able to transport more renewable energy than ever before over the 10 400 kilometers of its extra-high-voltage grid and up to 60% of its annual average electricity demand was met by its renewable feed-in of 60 TWh, all while lowering costs for congestion management (50Hertz, 2020).

03

Renewable technology and carbon reduction outlook

Renewable technology and carbon reduction outlook

Renewable energy, combined with intensified electrification, is key for the achievement of the Paris Agreement goals. To help enable the necessary transformation of the global energy sector, IRENA has developed an extensive and data-rich energy scenario database and analytical framework, which highlights immediately deployable, cost-effective options for countries to fulfil climate commitments and assesses the projected impacts of policy and technology change.

IRENA's analysis and its Transforming Energy Scenario show the important synergy between increasingly affordable renewable power technologies and the wider adoption of electric technologies for end-use applications, especially in transport and heat. This chapter will discuss in detail the following aspects: i) the key drivers of the energy transformation; ii) how the share of renewable energy in final energy consumption, the share of renewable energy in electricity generation and the electrification of final uses of energy can all be improved with a focus on cost, performance and deployment; iii) how electrification can transform end-use sectors (industry, buildings and transport) and can be used as an input for industrial processes; iv) the investment needs to achieve the energy transformation case, globally and regionally; v) the available alternatives to promote decarbonisation of final energy consumption that cannot be electrified; and vi) the available solutions for hard-to-decarbonise sectors (e.g. shipping, construction, aviation) that can be deployed in parallel to the Transforming Energy Scenario by 2050 to reduce emissions to net zero by 2050.

Box 1. IRENA's scenarios and perspectives

IRENA's latest report, Global Renewables Outlook, presents four scenarios representing possible paths of the global energy transformation:

- **The "Planned Energy Scenario (PES)"** is IRENA's primary reference case. It provides 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). It would set the energy system on the path needed to keep the rise in global temperatures to well below 2°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.

Source. (IRENA, 2019b)

3.1 Key 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 established a clear goal to limit the increase in global temperature to "well below" 2°C, and ideally to 1.5°C, compared to pre-industrial levels, during this century. To realise this climate target, a profound transformation of the global energy landscape away from the consumption of fossil fuels and towards cleaner renewable forms of energy is critical.

Such a transformation is possible by rapidly replacing conventional fossil fuel generation and uses with low-carbon technologies. IRENA's energy transformation roadmaps provide an ambitious, yet technically and economically feasible, pathway for making this transformation and creating a more sustainable clean energy future.

However, the reduction of carbon emissions is not the only reason why the world should embrace the energy transformation. Figure 4 (below) outlines other important drivers.

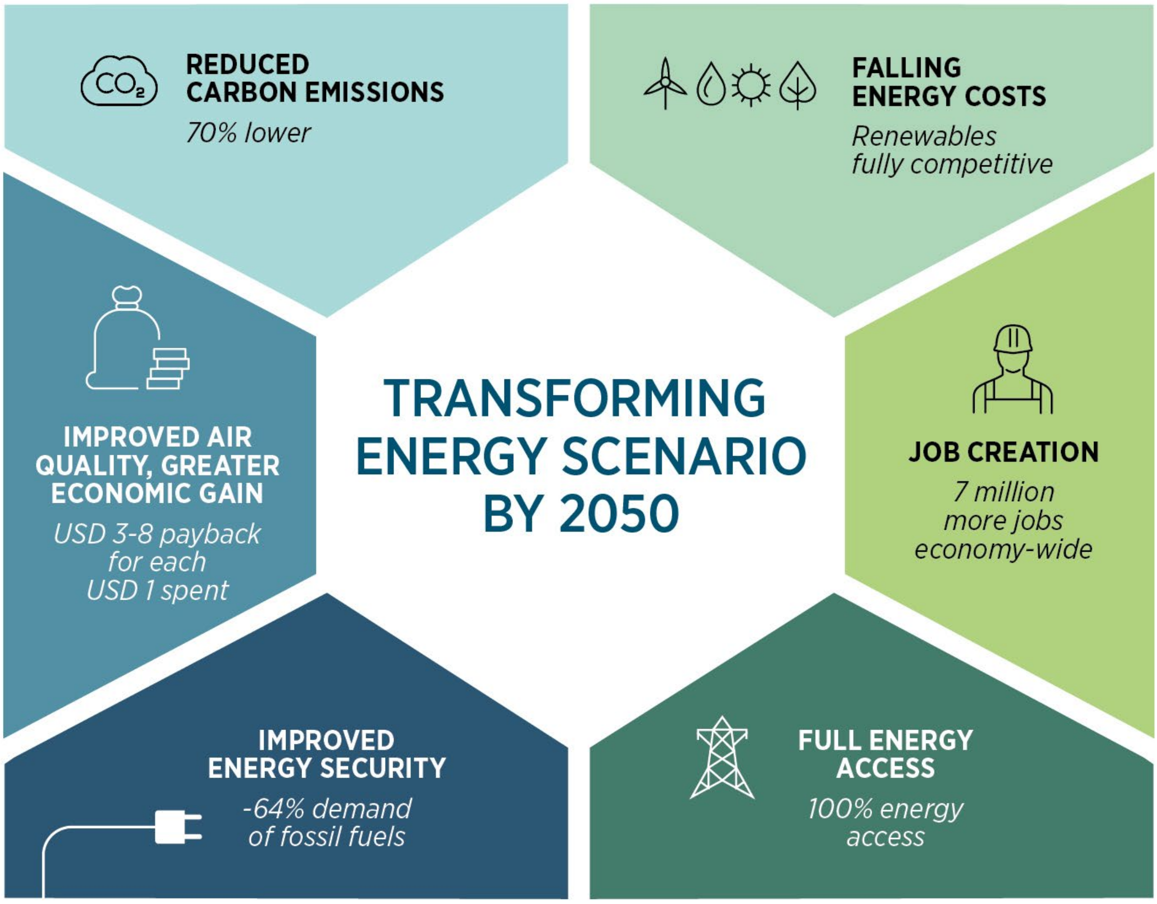


Figure 4. Key drivers for the energy transformation
Source. (IRENA, 2020b)

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, leading to a temperature increase of more than 3°C above pre-industrial levels. This case would mean that governments were failing to meet the commitments they made in signing the Paris Agreement.

Figure 5 shows the possible paths of annual energy-related CO_2 emissions and reductions as per three scenarios: the Baseline Energy Scenario (indicated by the orange line); the Planned Energy Scenario (indicated by the yellow line); and IRENA's energy transformation pathway, the Transforming Energy Scenario (indicated by the blue line).

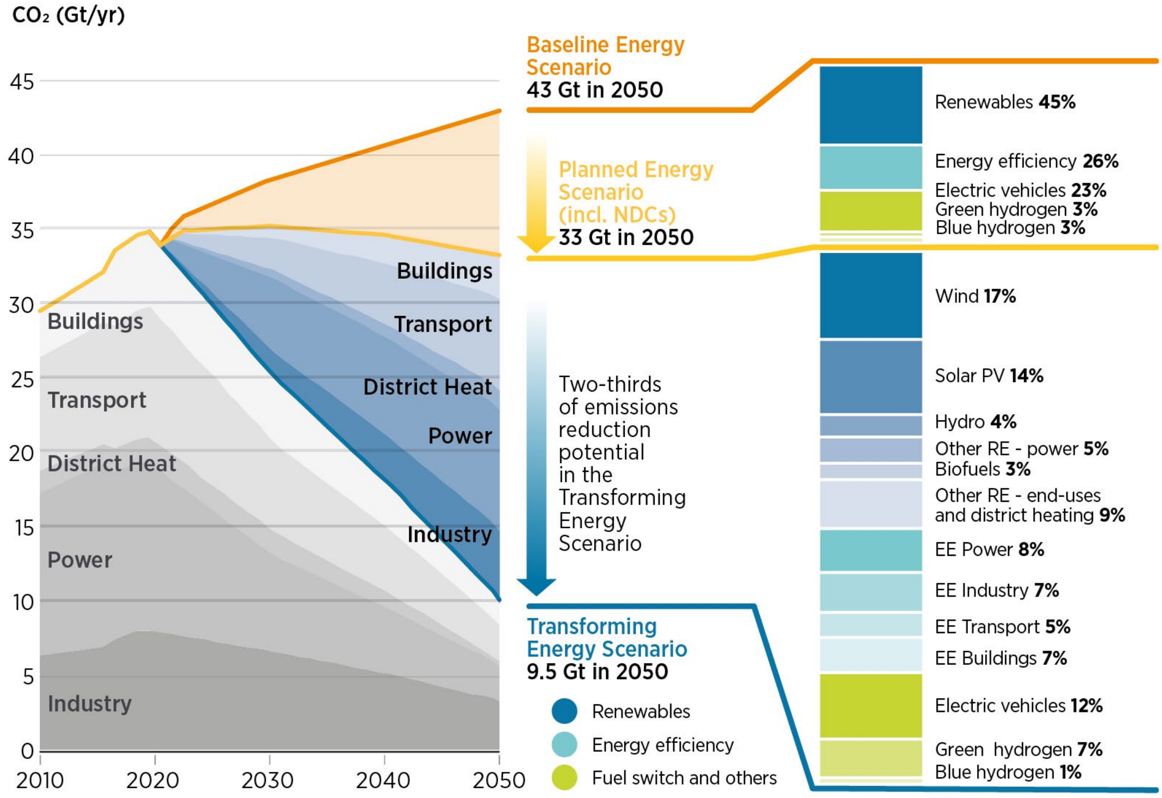


Figure 5. Annual energy-related CO_2 emissions and mitigation contributions by technology in the Baseline Energy Scenario, the Planned Energy Scenario and the Transforming Energy Scenario (2010-2050)
Source. (IRENA, 2020b)

In the Baseline Energy Scenario, energy-related emissions would 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. If the plans and pledges of countries are met as reflected in the Planned Energy Scenario, then energy-related CO_2 emissions would increase each year until 2030, before dipping slightly by 2050 to just below today's level. However, to meet the Paris Agreement target of limiting the global temperature rise to well below 2°C and towards 1.5°C, annual energy-related CO_2 emissions would need to fall more than 70% from now until 2050. Achieving these emissions reductions requires an acceleration across a spectrum of sectors and technologies, ranging from rapid deployment of renewable power generation capacities such as wind and solar PV, 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 and biomass), energy efficiency (e.g. thermal insulation of buildings and process improvement) and infrastructure investment (e.g. power grids and 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. Of the remaining 9.5 Gt of energy-related CO_2 emissions in 2050, just under one-quarter would be emitted for both electricity generation and transport, one-third in industry, 5% in buildings and the remaining 15% in other sectors (agriculture and 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.

3.2 Global pathway and decarbonising with renewables

Under current and planned policies in the Planned Energy Scenario, the total share of non-biomass renewable energy in the total primary energy supply (TPES) would only increase from around 5% to 17%, while under the Transforming Energy Scenario it increases to 42% (IRENA, 2020a) (Figure 6). Renewable energy use in absolute terms, excluding biomass, would increase from 25 exajoules (EJ) in 2017 to 225 EJ in 2050 in the Transforming Energy Scenario. TPES would also fall slightly below 2017 levels, despite significant population and economic growth.

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 would result in a decline of 0.2% per year to 2050.

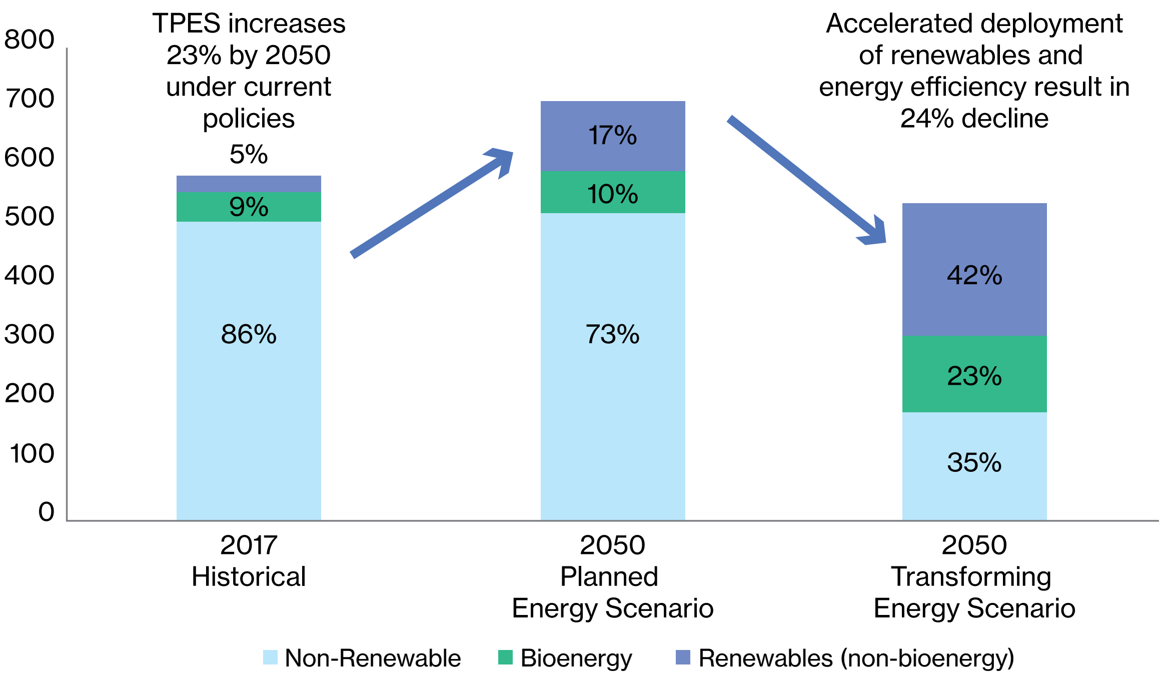


Figure 6. The global energy supply must become more efficient and more renewable
Source. Based on (IRENA, 2020b)

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 (of which 7% is from bioenergy and 79% from non-bioenergy renewables). 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. For power generation, solar PV and wind energy would lead the way. Wind power would supply more than one-third of total electricity demand. Solar PV power would follow, supplying 25% of total electricity demand (Figure 7), which would represent more than a 10-fold rise in solar PV's share of the generation mix by 2050 compared to 2017 levels. To achieve that generation mix, much greater capacity expansion would be needed by 2050 for solar PV (8 519 GW) than for wind (6 044 GW).

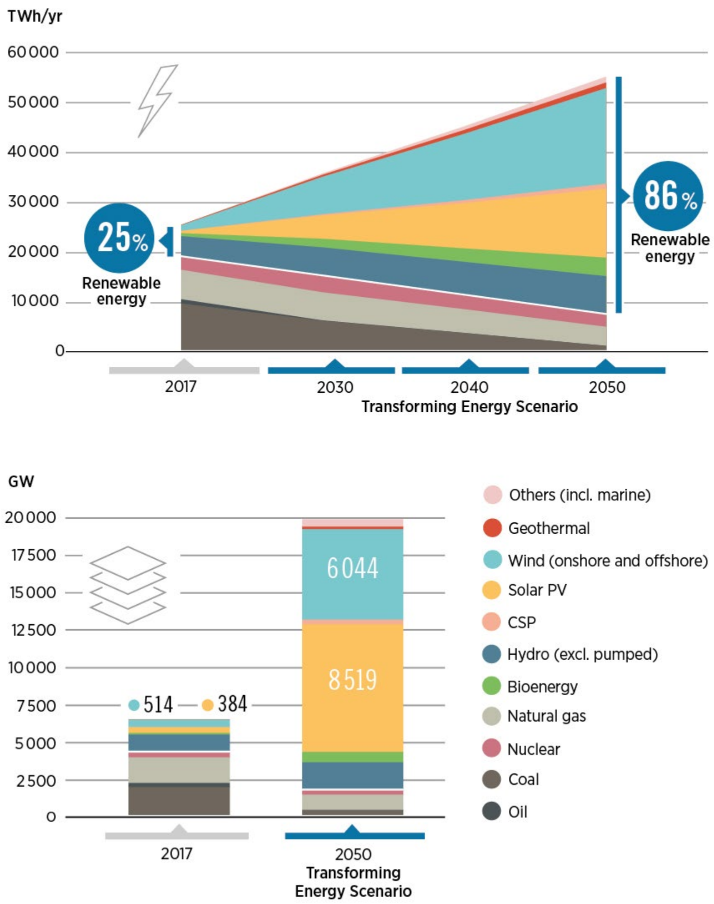


Figure 7. Breakdown of electricity generation and total installed capacity by source, 2017-2050

Source. (IRENA, 2020b)

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%. **Increasingly, electrification with renewables is seen as a major solution, and the contribution of renewable electricity will be the single largest driver for change in the global energy transformation.** The share of electricity in total final energy use would increase from just 20% today to 49% by 2050. The share of electricity consumed in industry and buildings would double to reach 42% in industry and 68% in buildings in 2050, and in transport it increases from just 1% today to over 40%. Other subsectors or activities would also see significant increases in the share of electricity use. Some of the largest growth would be seen in the buildings sector for space heating and cooking, and in the transport sector for passenger and road freight (IRENA, 2020a).

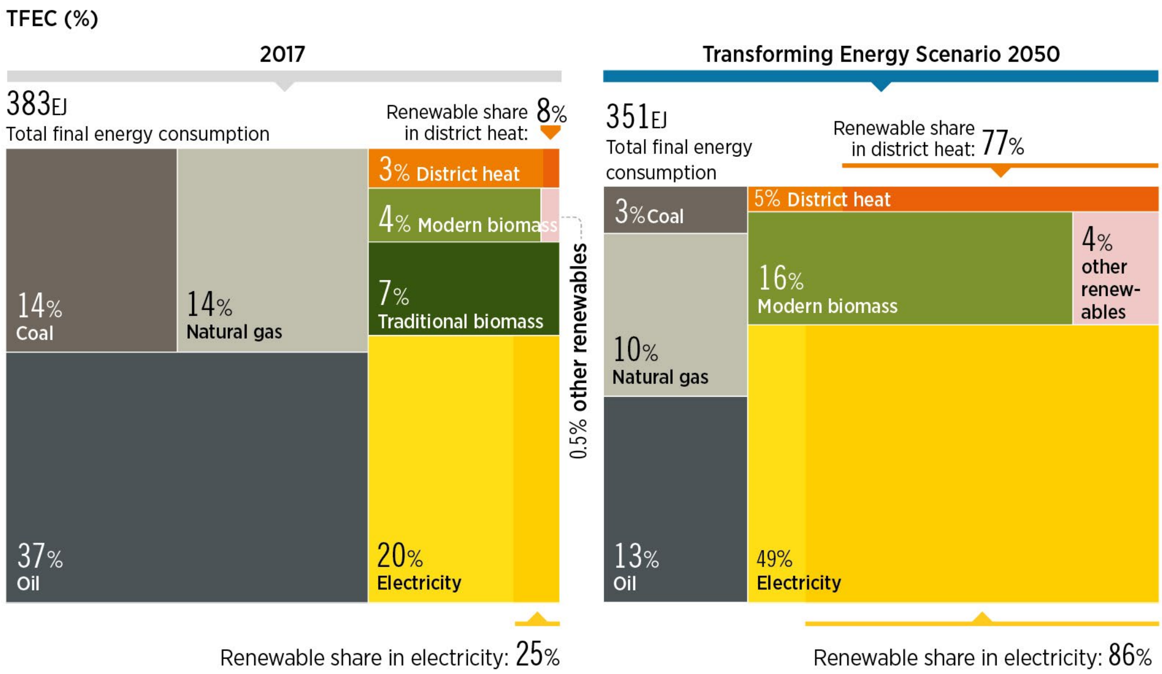


Figure 8. Electricity becomes the main energy carrier in energy consumption by 2050
Source. (IRENA, 2020b)

Power sector

The energy transformation outlined in the Transforming Energy Scenario would require the almost complete decarbonisation of the electricity sector by 2050. In addition, electricity consumption in end-use sectors would more than double compared to 2017 and reach 55 000 TWh by 2050, driving increased power demand to be met with renewables (Figure 9). However, the shift to electrification of end uses brings major increases in energy efficiency. Heat pumps, for example, are two to four times more efficient than conventional heating systems.

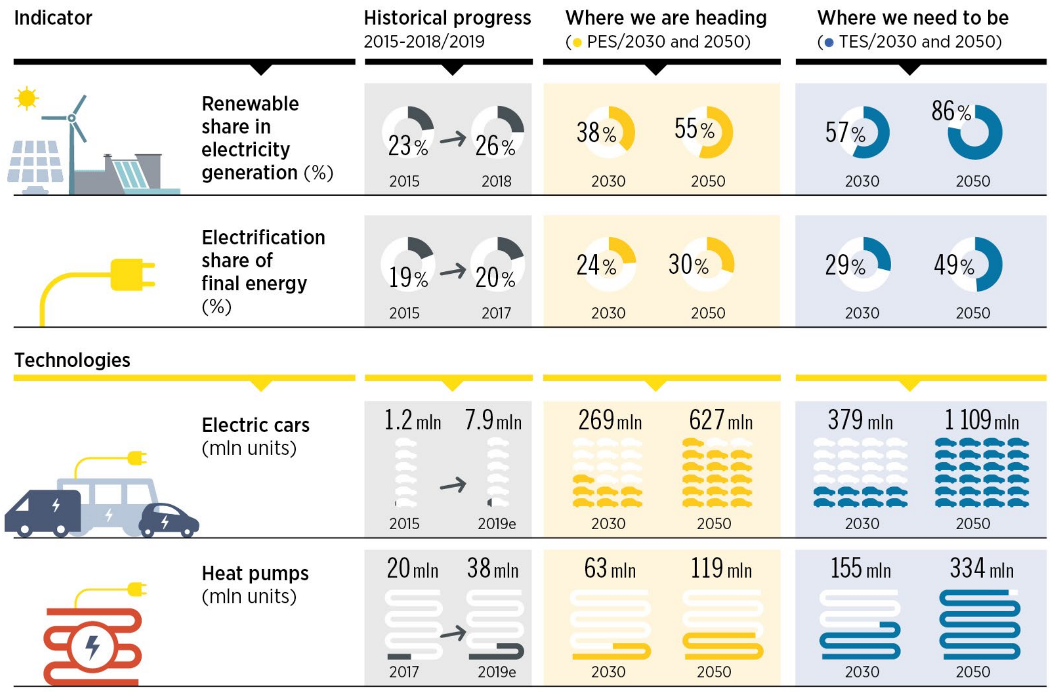


Figure 9. Power sector key indicators

Source. (IRENA, 2020b)

With high shares of renewable electricity, flexibility is key to guarantee the stability of the power system. That flexibility will be enabled by current and ongoing innovations in 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 10). 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 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. Natural gas power plants could also have a role balancing the system and addressing fluctuating output from renewables, such as wind and solar. Natural gas applications and technologies can also support decentralised energy systems and can be used in small-scale hybrid appliances combined with renewable sources, such as solar gas water heaters that use natural gas only when sunshine is insufficient. Similarly, Power-to-Gas allows for integration of renewable generation by converting surplus renewable generation to hydrogen using electrolysers and storing the hydrogen in natural gas infrastructure for later use as an emissions-free source of energy. Renewable natural gas (also called bio-methane) provides another pathway to a low carbon future as a renewable source of heating and transportation fuel (International Gas Union, 2015).

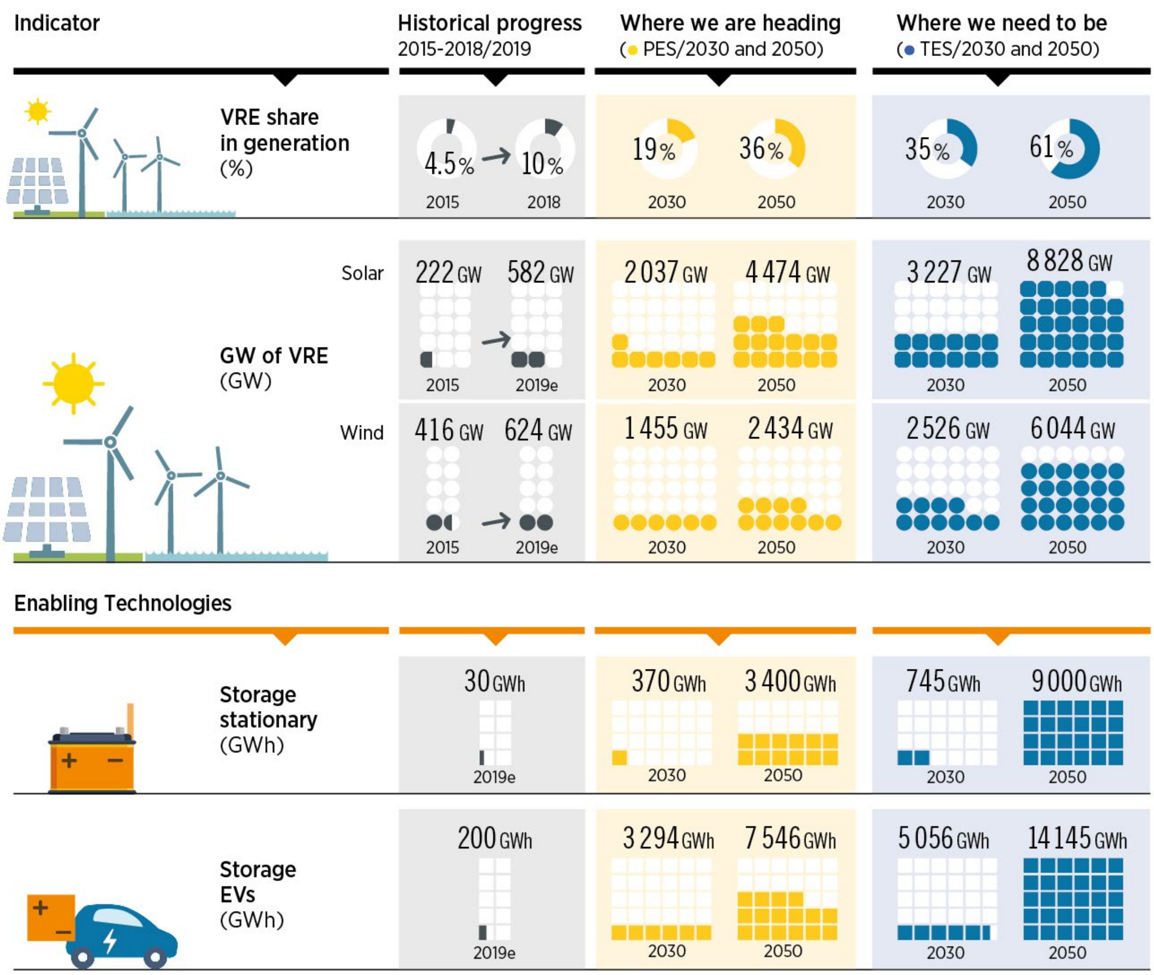


Figure 10. VRE share in generation and capacity, storage technologies
Source. (IRENA, 2020b)

3.3 Transforming and electrifying the end-use sectors

The most important synergy of the global energy transformation comes from combining low-cost renewable power technologies with the wider adoption of electric technologies for end-use applications in transport and heat. The renewable energy and electrification synergy alone can provide two-thirds of the emissions reductions needed to meet the goals of the Paris Agreement. This section details the key changes needed in the main energy-consuming end-use sectors of transport, industry and buildings (residential, commercial and public) over the period to 2050 in the Transforming Energy Scenario (IRENA, 2020b).

Transport sector

The Transforming Energy Scenario shows that widespread electrification and other low-carbon approaches would cut transport emissions to just 2.4 Gt CO_2 annually by 2050, nearly 80% less than 2016 levels. Electrification of transport increases significantly in the scenario, which also assumes that hydrogen produced from renewable electricity will be used a transport fuel.

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. In addition to reducing emissions from the transport sector, EVs present a viable opportunity to introduce much higher shares of renewables into the overall power generation mix. Indeed, 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.

Overall, the combination of the low-carbon technology options in the Transforming Energy Scenario leads to a drop of nearly 70% in oil consumption by 2050 compared to 2017. The share of electricity in all of transport sector energy rises from just above 1% in 2017 to 43% in 2050 (IRENA, 2020b).

Buildings sector

Under the Transforming Energy Scenario, the buildings sector would increase its share of non-biomass renewable energy to 65% by 2050, and electricity demand in the buildings sector would increase by 80% by 2050. The increase occurs despite improvements in appliance efficiency because of strong growth in electricity demand (particularly in emerging economies) and increases in the electrification of heating and cooling. The Transforming Energy Scenario expects deployment of highly efficient appliances, including smart home systems with advanced controls for lighting and air conditioning, improved heating systems and air conditioners, better insulation, replacement of gas boilers by heat pumps and other efficient boilers, and retrofitting of old and new buildings to make them more energy efficient. **The shift in cooking technologies from fuel combustion to electricity would also promote renewables, due to**

the high share of renewable power in the electricity supply. Electric stoves, such as induction cookstoves, can cut the energy demand of cooking by three to five times. In addition, more renewables-based stoves that use modern biofuels and solar energy could be deployed (IRENA, 2020b).

Industry sector

Industry is the second-largest emitter of energy-related CO_2, after the power sector, and is responsible for a little under one-third of these emissions worldwide (when including process emissions). But in 2017, renewables provided only around 13% of the industry sector's energy demand, and most of this was bioenergy. Electricity supplied 24% of the energy consumed by the sector. The Transforming Energy Scenario reduces the sector's emissions by 60% by 2050; however, industry would still emit more than 3 Gt of CO_2 in 2050 and would become the largest source of emissions. Within the sector, chemical, petrochemical and steel are among the largest emitters, because they employ energy-intensive and high-temperature processes that are difficult to decarbonise. **Under the Transforming Energy Scenario, industry would increase its share of non-biomass renewable energy to 39% by 2050, and electricity would meet more than 40% of industry's energy needs by 2050.** While renewable electricity would become the largest source of renewable energy consumed in the sector, bioenergy sources would remain the largest source of renewable heat by a large margin and would be based largely based on residues used for direct heat and combined heat and power (CHP) (IRENA, 2020b).

Energy system overview

The energy transformation will require widespread and profound changes in all parts of the energy system. Figure 11 shows some of the key energy system indicators that can be used to track the progress of the 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.

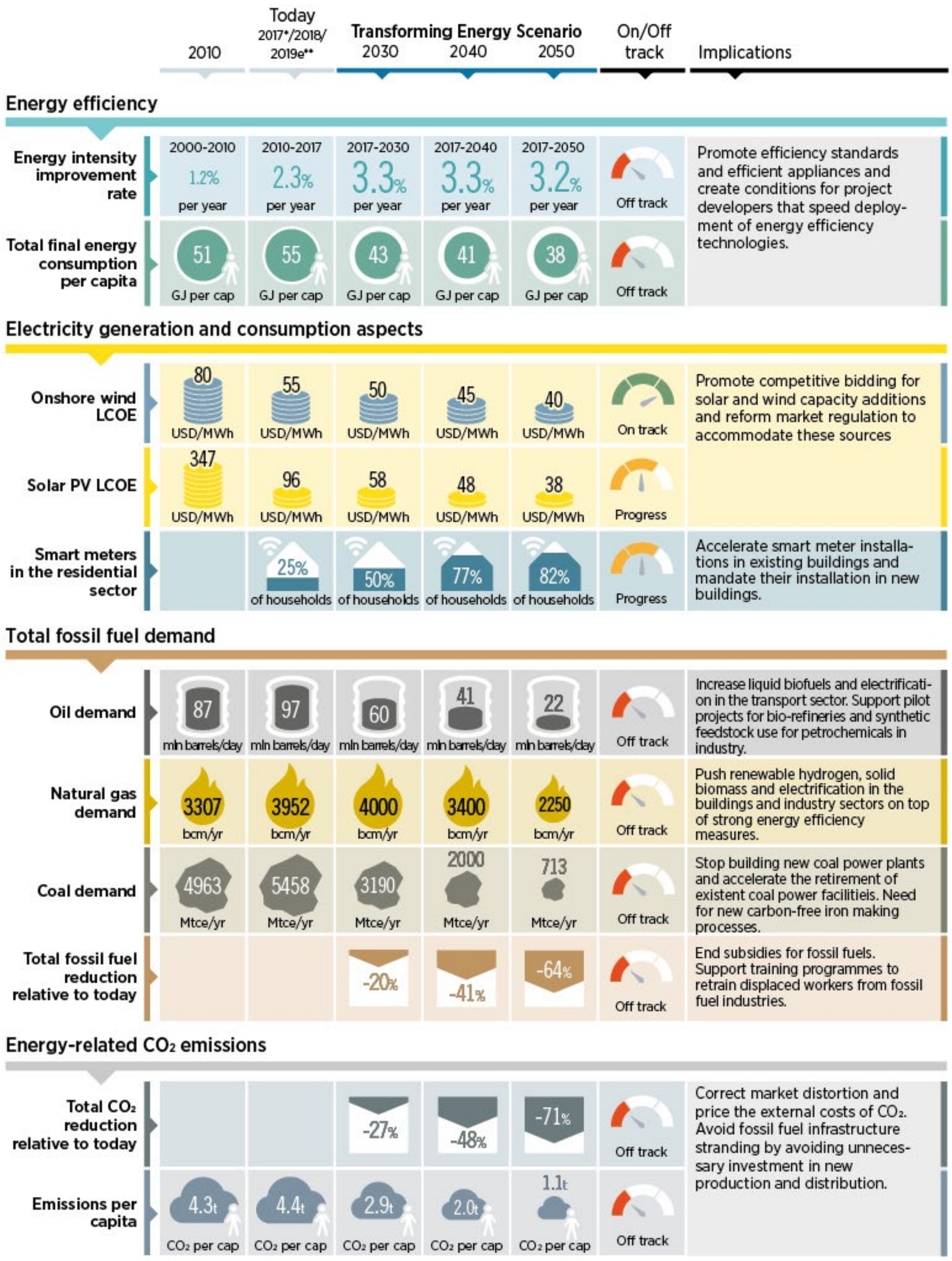


Figure 11. Progress that is needed for key indicators to achieve the Transforming Energy Scenario

Source. (IRENA, 2020b)

3.4 Investments

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. 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 (IRENA, 2020b).

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.

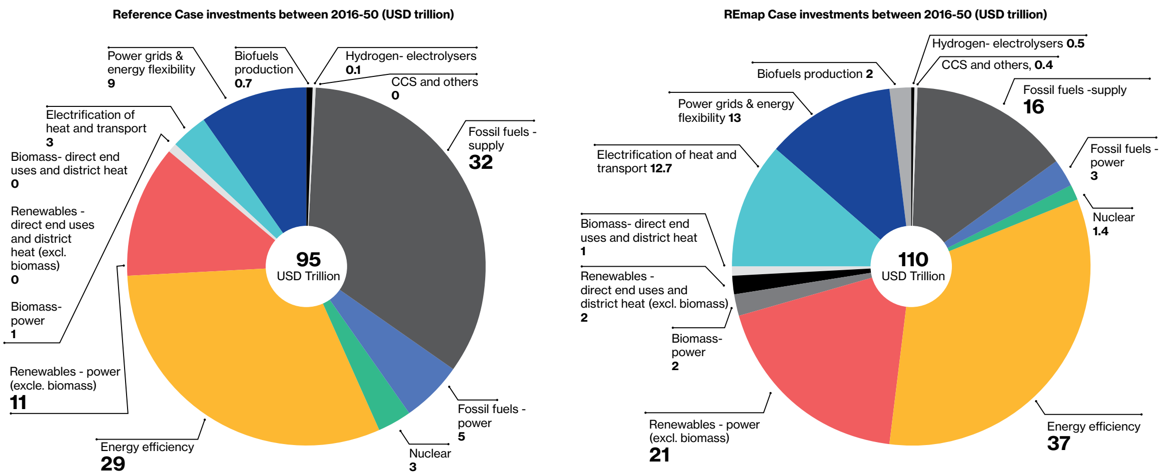


Figure 12. Cumulative energy sector investments over the period to 2050 under the Planned Energy Scenario and the Transforming Energy Scenario
Source. (IRENA, 2020b)

The benefits for accelerating renewables deployment and efficiency measures are 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 13). Or to put it in cumulative terms, the Transforming Energy Scenario would cost an additional USD 19 trillion over the period to 2050 but would bring benefits of between USD 50 trillion and USD 142 trillion in reduced environmental and health externalities. Another way to look at costs is how much it takes to mitigate one tonne of CO_2 over the period, which would be USD 34/t CO_2 for the Transforming Energy Scenario.

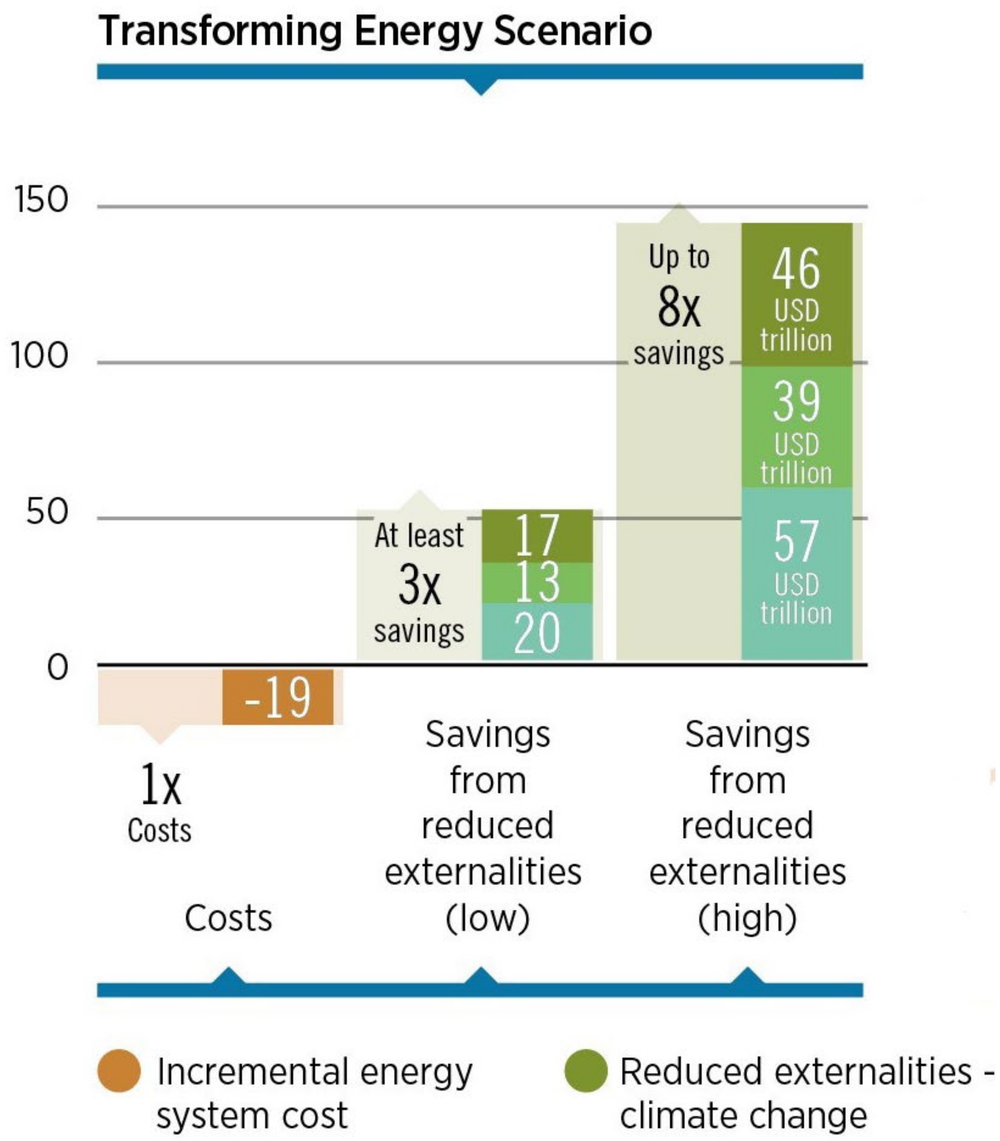


Figure 13. Cumulative system costs and savings from reduced externalities for the Transforming Energy Scenario for the period to 2050 (USD trillion)
Source. (IRENA, 2020b)

3.5 Decarbonisation of final energy consumption that cannot be electrified

IRENA's Transforming Energy Scenario outlines a climate-friendly pathway with energy-related CO_2 emissions reductions of 70% by 2050 compared to 2019 levels.

However, in this scenario, 9.5 Gt (or 10.4 Gt including industrial processes) of energy-related CO_2 emissions remain in 2050. Around 2.9 Gt of process emissions were emitted globally in 2016, which in the Planned Energy Scenario would 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.

To stop global temperatures from rising, emissions must eventually reach zero, or net zero, by the second half of this century. "Reaching zero" requires the complete decarbonisation of all energy and industrial processes so that no CO_2 is emitted at all, while the "net zero" emissions approach would require offsetting any remaining emissions through the use of CDR. Examples of CDR include reforestation, afforestation, direct air capture and bioenergy CCS.

This paper considers the "reaching zero" approach. Figure 14 outlines, by technology category, the reductions that would be needed by sector.

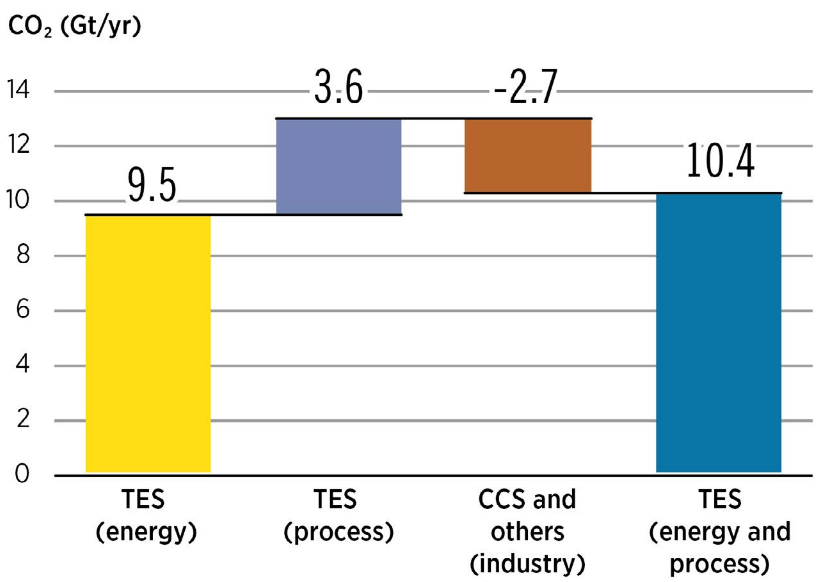


Figure 14a. Remaining energy and process-related CO_2 emissions in the Transforming Energy Scenario and Deeper Decarbonisation Perspective "zero" to reduce energy and process emissions to zero latest by 2060 ($GtCO_2$)
Source. (IRENA, 2020b)

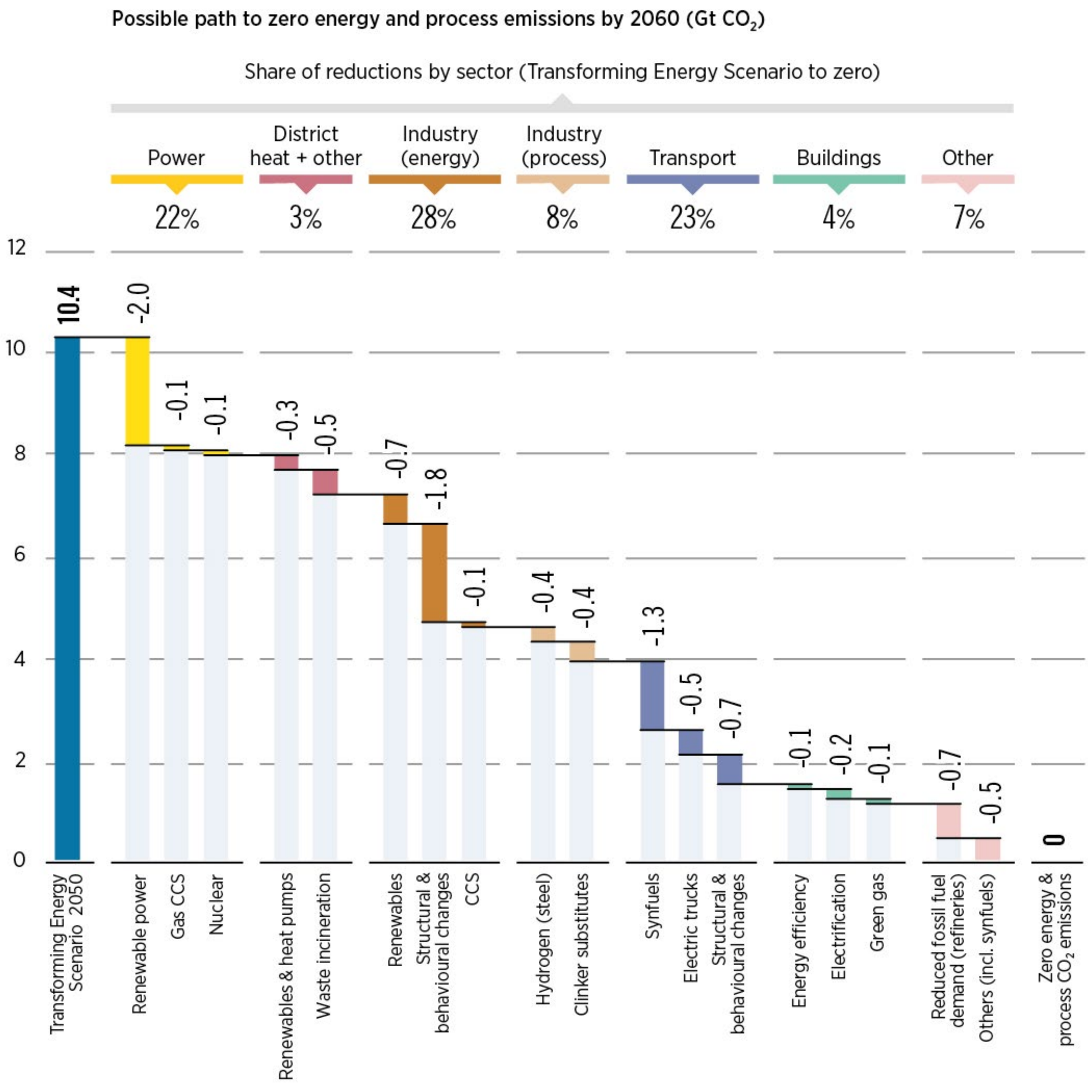


Figure 14b. Remaining energy and process-related CO_2 emissions in the Transforming Energy Scenario and Deeper Decarbonisation Perspective "zero" to reduce energy and process emissions to zero latest by 2060 ($GtCO_2$)

Source. (IRENA, 2020b)

In the Transforming Energy Scenario, total annual CO_2 emissions are reduced by 26.3 Gt, with almost half of the reductions coming from increases in renewable energy, followed by a 24% reduction from energy efficiency. The efficiency reductions come largely from technical efficiency measures but also from structural changes such as the circular economy and other measures that reduce consumption of energy-intensive and carbon-intensive products. Of the remaining emissions reductions, 11% 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. Renewables, energy efficiency and other measures each contribute about one-third of the emissions reductions. Of the other measures, green hydrogen (which includes synthetic fuels and use as a feedstock) plays the most important role.

The Deeper Decarbonisation Perspective "zero" would cost an additional USD 26 trillion to achieve fully zero emissions (with no carbon offsets) on top of the Transforming Energy Scenario costs of USD 19 trillion. Therefore, the total costs would be 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 15).

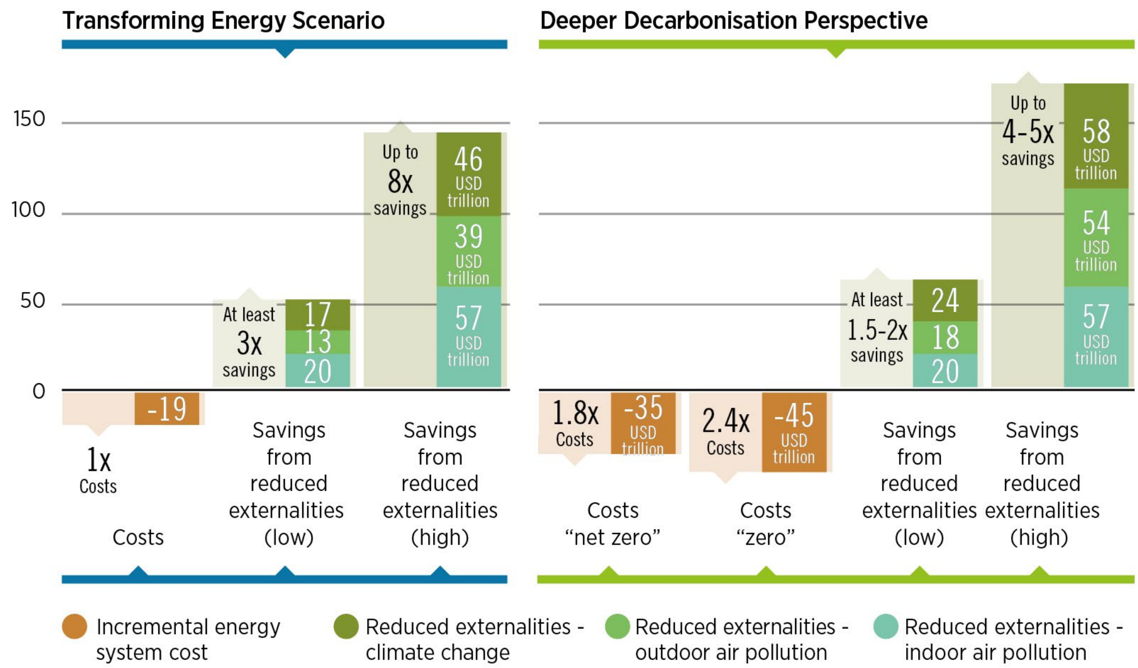


Figure 15. Cumulative costs and savings for the Deeper Decarbonisation Perspective "zero", 2020-2050 (TES), 2020-2060 (DDP) (trillion USD2015)

Source. (IRENA, 2020b)

The overall costs do not account for the fact that many of the clean energy technologies are much cheaper than fossil fuel alternatives as shown in Figure 16. Another way to look at it is in the cost to mitigate one tonne of CO_2 over the period. Many of the technologies that result in reductions in the Transforming Energy Scenario are cheaper than the fossil fuel alternatives. Because the Deeper Decarbonisation Perspective has to address remaining emissions in challenging sectors, and eventually reduce those to zero, it has higher costs compared to the Transforming Energy Scenario.

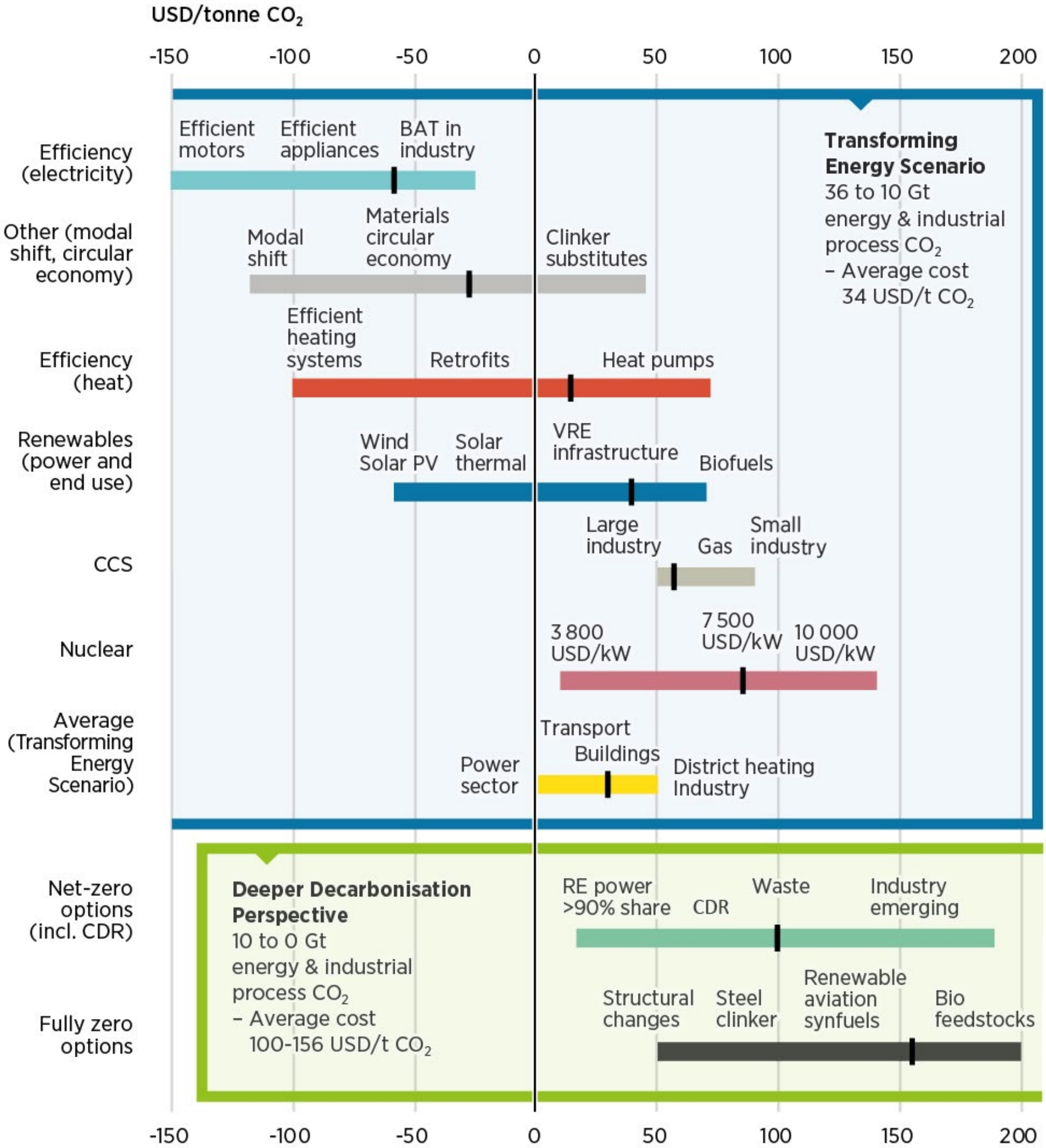


Figure 16. Mitigation costs for select technologies and groupings, 2050

Source. (IRENA, 2020b)

Box 2. IRENA's "Reaching Zero with Renewables - Eliminating CO_2 Emissions in Industry & Transport"

Effectively tackling climate change will require the complete decarbonisation of all sectors of the economy by around 2060. This will be very challenging, especially in industry and transport sectors where viable options are currently limited, and will require a complete change of mindset compared to merely reducing emissions.

IRENA has explored how the world can achieve zero emissions by 2060 in the 2020 report, Reaching Zero with Renewables – Eliminating CO_2 Emissions in Industry & Transport (IRENA, 2020c). The report shows that renewable energy can reduce CO_2 emissions in end-use sectors that are usually qualified as "hard-to-decarbonise" or "hard-to-abate", such as some industry and transport subsectors. Decarbonising these sectors can be accomplished by expanding direct electrification while also increasing the share of renewables in the electricity supply. This however, should be coupled with several additional options, such as indirect electrification via the production of hydrogen through renewable power and the greater use of biomass (including biofuels) and green gas. Other solutions, such as energy efficiency and the circular economy, are still worth exploring as interim solutions and to reduce the scale of the challenge. The falling costs of renewable power generating technologies, and the vast applications of these additional options, highlight the value of focusing more public attention on creating a path towards zero emissions by 2060.

Yet, some key challenges remain. The first is technology uncertainty. Achieving more clarity on these pathways is thus be essential for promoting investment and technological scale up. The second is the relatively high capital costs of many of the technological solutions. Increased support for innovation across the entire innovation chain (including RD&D) and incentives for scale-up are needed to drive cost reductions.

Source: (IRENA, 2020c)

3.6 G20 overview

The Group of Twenty (G20) members account for 85% of the global economy, two-thirds of the global population and almost 80% of global energy consumption. The energy mix in G20 economies is quite varied; however, most countries currently rely on a high share of fossil fuels in their total energy supply and thus are responsible for more than 80% of global CO_2 emissions. Yet G20 economies have also become leaders in fostering cleaner energy systems, and their energy transition will shape global energy markets and determine both emissions and sustainable pathways globally.

Table 2 presents the evolution of key energy sector indicators in the G20 from today's levels in the Transforming Energy Scenario (to 2030, 2040 and 2050). The Transforming Energy Scenario leads to lower levels of supply and consumption of energy in absolute terms. By 2050, 51% of final energy consumption is electrified, with the highest share in buildings at 65%, followed by transport at 45% and industry at 44%. Renewable energy would have a prominent role in the electricity mix, with solar PV and wind (onshore and offshore) leading the way in absolute terms.

		Where we need to be		
	2017	**2030 (TES)**	**2040 (TES)**	**2050 (TES)**
Energy (EJ)				
Supply (TPES)	586	450	437	419
Consumption (TFEC)	383	303	292	275
Electricity share in final energy consumption				
End-use consumption	20%	30%	40%	51%
Industry	24%	31%	37%	44%
Transport	1%	12%	28%	45%
Buildings	31%	48%	56%	65%
Renewable installed capacity (GW)				
Bioenergy	108	300	415	544
Hydropower	1150	1167	1330	1473
Solar PV	386	2955	5317	7672
Wind	515	2379	3972	5426

Table 2: Evolution of key energy indicators in G20 for 2017 and for the Transforming Energy Scenario in 2030-2040 and 2050

Source. data extracted from (IRENA, 2020b)

Setting G20 countries on the Transforming Energy Scenario pathway would require a total cumulative energy sector investment of USD 79 trillion to 2050 (Table 3). Investments in renewable energy, electrification and energy efficiency would amount altogether to USD 63 trillion to 2050. The shift to greater investment in electrification reflects its importance in powering an increasingly connected and digitalised global economy.

	Cumulative investments (USD billion) 2016-50 (TES)
Supply side (including fossil fuels)	2025
Power generation (thermal and nuclear)	3268
Renewables	22269
Energy efficiency	29596
Electrification	11407
CCS & others	320
Power grids and energy flexibility	10443
Total	**79328**

Table 3: Cumulative investments in G20 countries in the Transforming Energy Scenario (USD billion- 2016-2050)

Source. data extracted from (IRENA, 2020b)

04

Socio-economic footprint of the G20 energy transition

A true and complete energy transition includes both the energy transition and the socio-economic system transition, and the linkages between them. Therefore, a wider picture is needed that views energy and the economy as part of a holistic system.

Socio-economic footprint analyses (IRENA, 2016, 2019f, 2020b) have captured an increasingly comprehensive picture of the impact of the energy transition. For these analyses, IRENA has undertaken a macroeconometric approach (using the E3ME model) that links the energy system and the world's economies within a single and consistent quantitative framework. The approach analyses variables such as GDP, employment and welfare (Figure 17). The results from the socio-economic footprint analysis of the Transforming Energy Scenario globally show an additional net 15 million jobs and a 13.5% improvement in welfare by 2050, as well as an annual average boost of 2% in GDP between 2019 and 2050 compared to the Planned Energy Scenario.

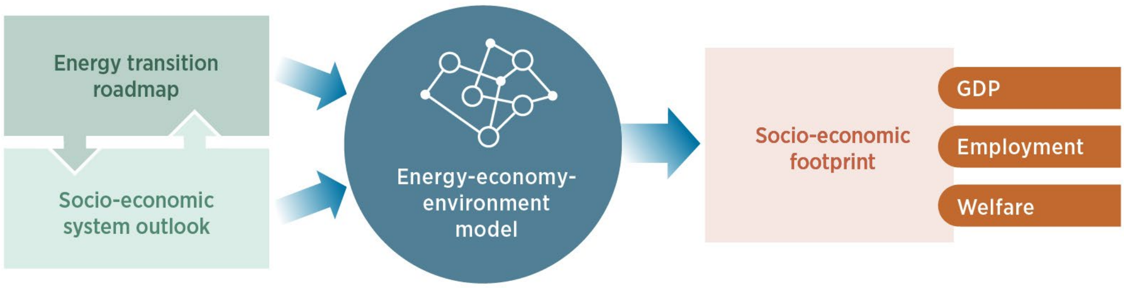


Figure 17. Estimating the socio-economic footprint of transition roadmaps
Source. (IRENA, 2020b)

This chapter presents the regional impacts of the Transforming Energy Scenario for the G20 in terms of GDP, jobs and welfare in IRENA's socio-economic footprint analysis.

4.1 Energy sector and renewable energy jobs in the G20

The energy transition implies deep changes in the energy sector, with strong implications for the evolution of jobs. While some technologies experience significant growth (e.g. renewable generation, energy efficiency and energy flexibility), others would be gradually phased out (e.g. fossil fuels), and all of this happens simultaneously with the evolution of energy demand.

Figure 18 presents the evolution of energy sector jobs in the G20 for both the Planned Energy Scenario and the Transforming Energy Scenario, by technologies. The Transforming Energy Scenario leads to a higher number of overall energy sector jobs than the PES, as declines in the number of fossil fuel jobs are more than offset by increases in jobs in renewable energy, energy efficiency and energy flexibility. By 2050, nearly 71 million people would be employed in the energy sector in the Transforming Energy Scenario, 46% in renewable energy, 25% in energy efficiency and 15% in energy flexibility. About 13% of energy jobs would still be in fossil fuels.

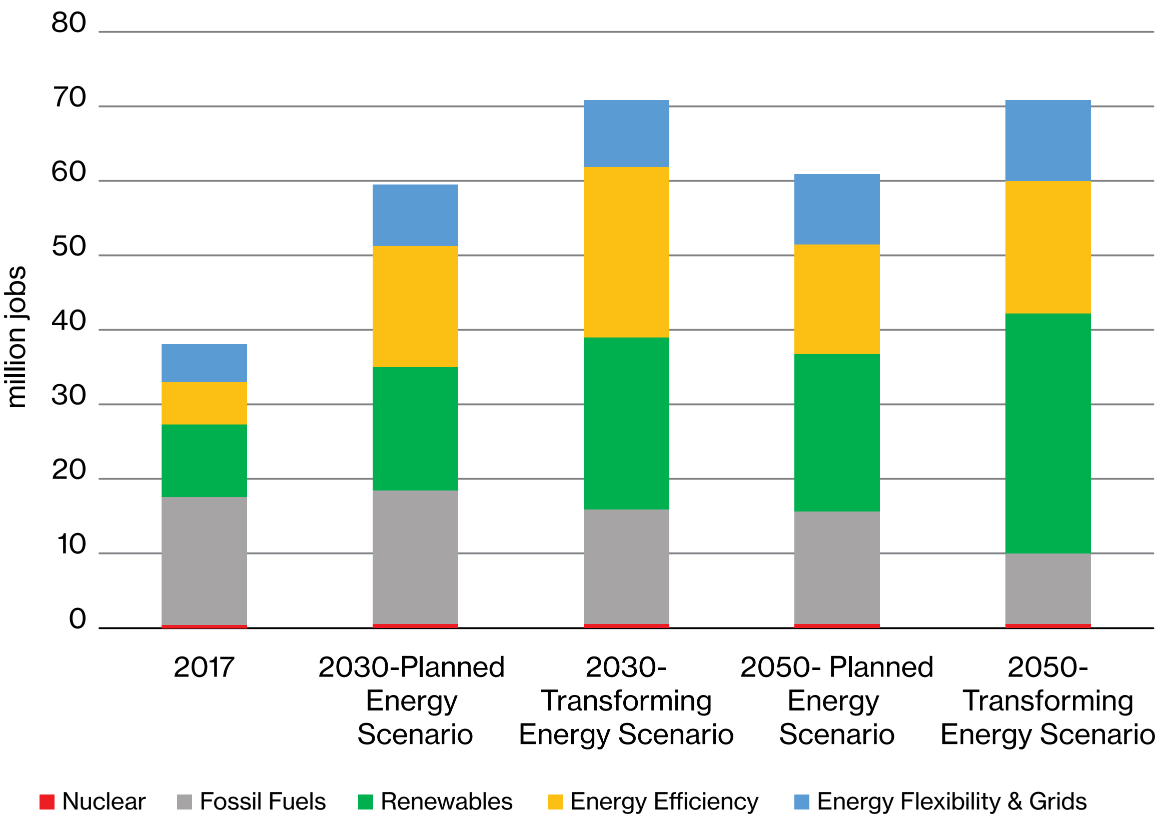
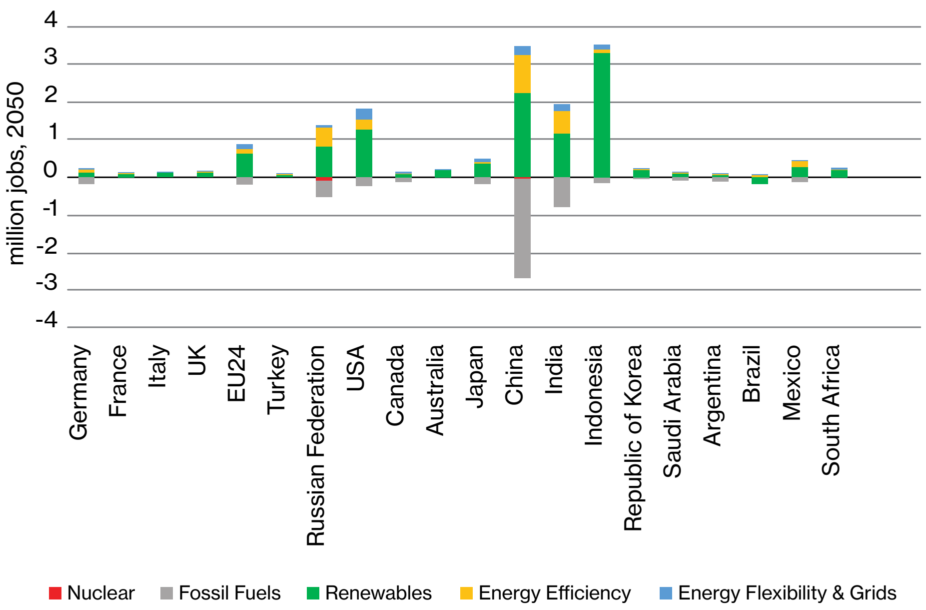


Figure 18. Evolution of energy sector jobs, by technology, under the Planned Energy Scenario and the Transforming Energy Scenario from 2017 to 2030 and 2050

Source. data extracted from (IRENA, 2020b)

To better appreciate the balance between gained and lost jobs when moving from the Planned Energy Scenario to the Transforming Energy Scenario, Figure 19 presents the difference in energy sector jobs by technology in 2050. Results are presented for the G20 and for each of the countries or regions within the G20 to show the important distributive elements. At the G20 level, renewables dominate the difference in jobs between the Transforming Energy Scenario and the Planned Energy Scenario with over 11 million jobs, followed by energy efficiency with over 3 million jobs and flexibility and grids with 1.4 million additional jobs. Fossil fuels lose 5.5 million jobs in the G20. In absolute terms, the loss of fossil fuel jobs is concentrated in few countries (mainly China, India and the Russian Federation). However, in relative terms to overall energy sector employment, other countries experience significant reductions in fossil fuel jobs (United States, Canada, Germany, EU24, Saudi Arabia, Argentina and Mexico). The overall energy sector balance (misalignments) changes significantly from country to country within the G20.



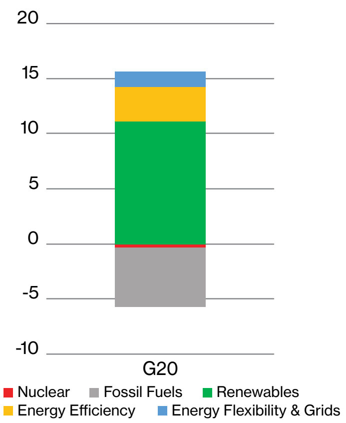


Figure 19. Difference of energy sector jobs, by technology, in 2050 between the Planned Energy Scenario and the Transforming Energy Scenario. Total G20 values and distribution within G20

Source. data extracted from (IRENA, 2020b)

IRENA monitors the evolution of renewable energy jobs (IRENA, 2019g), and projects the evolution under different transition scenarios. Figure 20 presents the evolution of renewable energy jobs in the Planned Energy Scenario and the Transforming Energy Scenario for the G20 during the transition, by technologies. The TES provides a significant increase (52%) in renewable energy jobs compared to the PES. By 2050, the Transforming Energy Scenario has 32.4 million people employed in renewables, 51% in solar energy, 26% in bioenergy, 17% in wind energy and just above 5% in hydro.

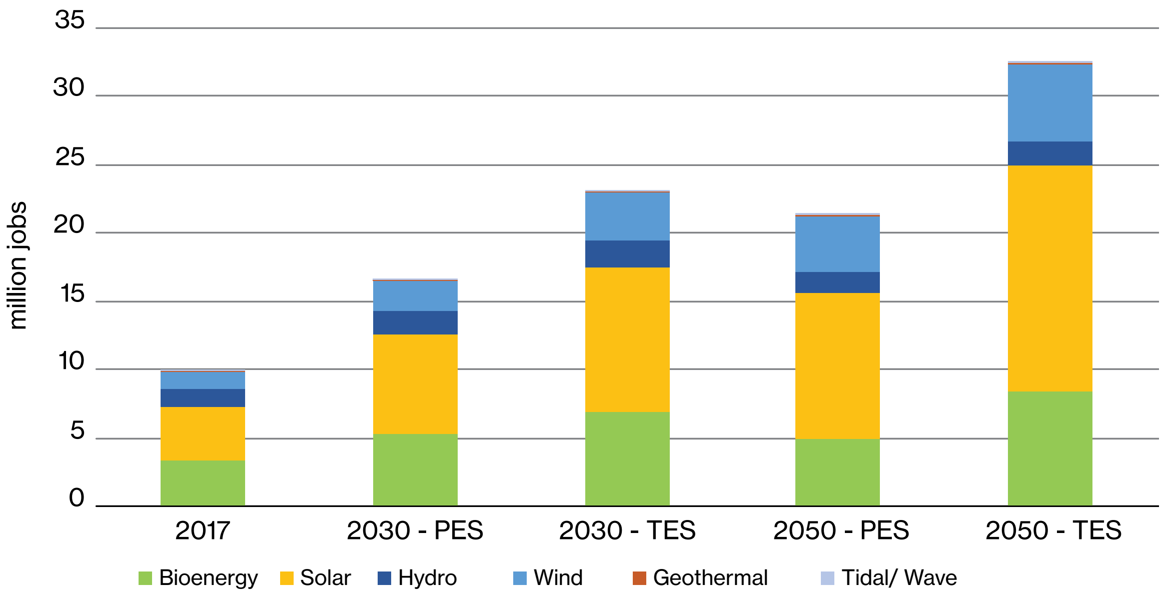


Figure 20. Evolution of renewable energy jobs, by technology, under the Planned Energy Scenario and the Transforming Energy Scenario from 2017 to 2030 and 2050
Source. (IRENA, 2020b)

For the year 2050, Figure 21 presents how the 32.4 million renewable energy jobs in the G20 are distributed by technologies and segments of the value chain: 33% in construction and installation, 24% in manufacturing, 20% in O&M and 22% in biomass supply.

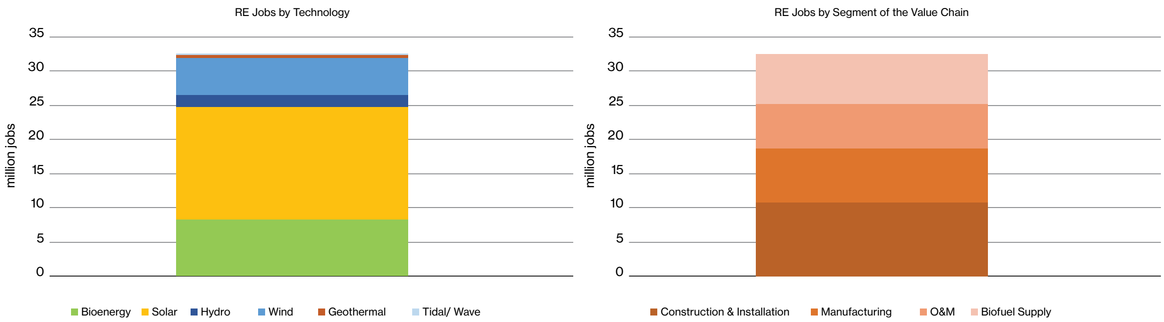


Figure 21. Distribution of G20 renewable energy jobs in 2050 under the Transforming Energy Scenario by technology and segments of value chain

Source. (IRENA, 2020b)

To inform educational planning to enable the transition, insights are needed about the distribution of these jobs in terms of occupational requirements. Figure 22 presents this information for a subset of renewable energy technologies[1]. Of these 22 million jobs, 77% are filled by workers and technicians. Just above 10% of those employed are experts, while about 9% are engineers and people with other higher degrees, and less than 5% are marketing and administrative personnel.

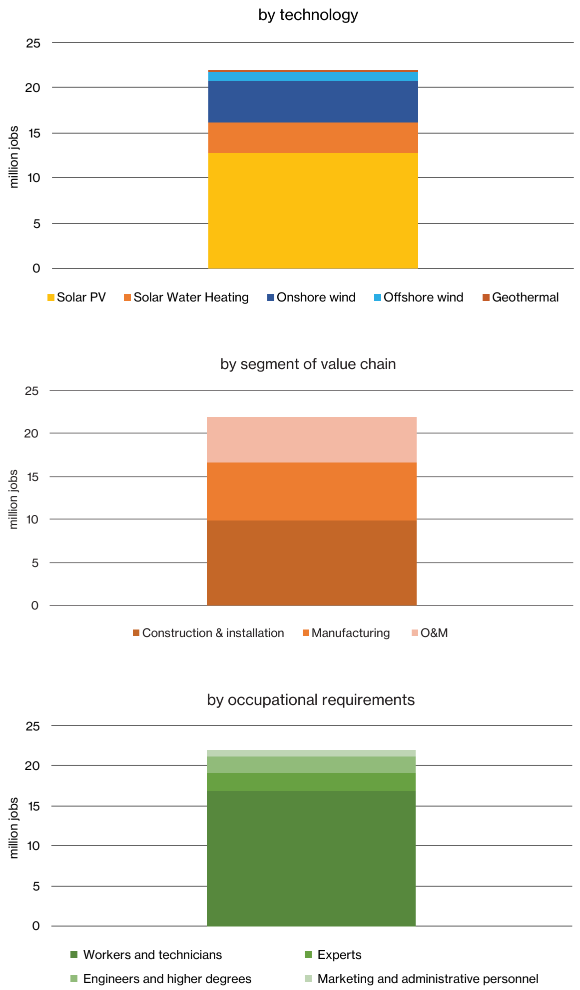


Figure 22. Distribution of a subset of G20 renewable energy jobs in 2050 under the Transforming Energy Scenario by technology, segments of value chain and occupational requirements
Source. Data extracted from (IRENA, 2020b)

[1] The included technologies are solar photovoltaics (PV), solar water heaters (SWH), onshore wind, offshore wind and geothermal, representing a total of around 22 million jobs (about a 68% of the total 32 million renewable energy jobs by 2050 in G20). These are the technologies for which skills requirements are properly characterised. The analysis draws from IRENA's workstream in leveraging local capacities. As leveraging analysis on additional technologies becomes available, the forecast on the required structure of skills can be completed.

4.2 Gross domestic product in G20

Figure 23 show the yearly evolution of the difference in GDP between the Planned Energy Scenario and the Transforming Energy Scenario up to 2050, as well as the impact from the different drivers of the GDP difference. The energy transition brings about a significant improvement in GDP, with the increase rising to 3% before 2040 and remaining there until 2050.

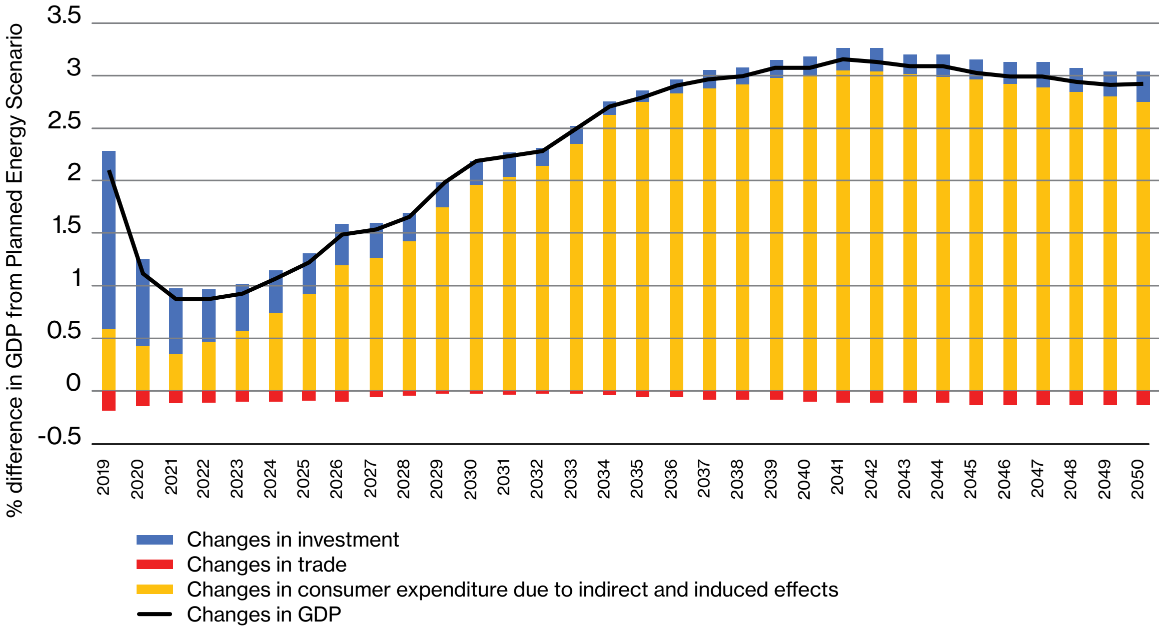
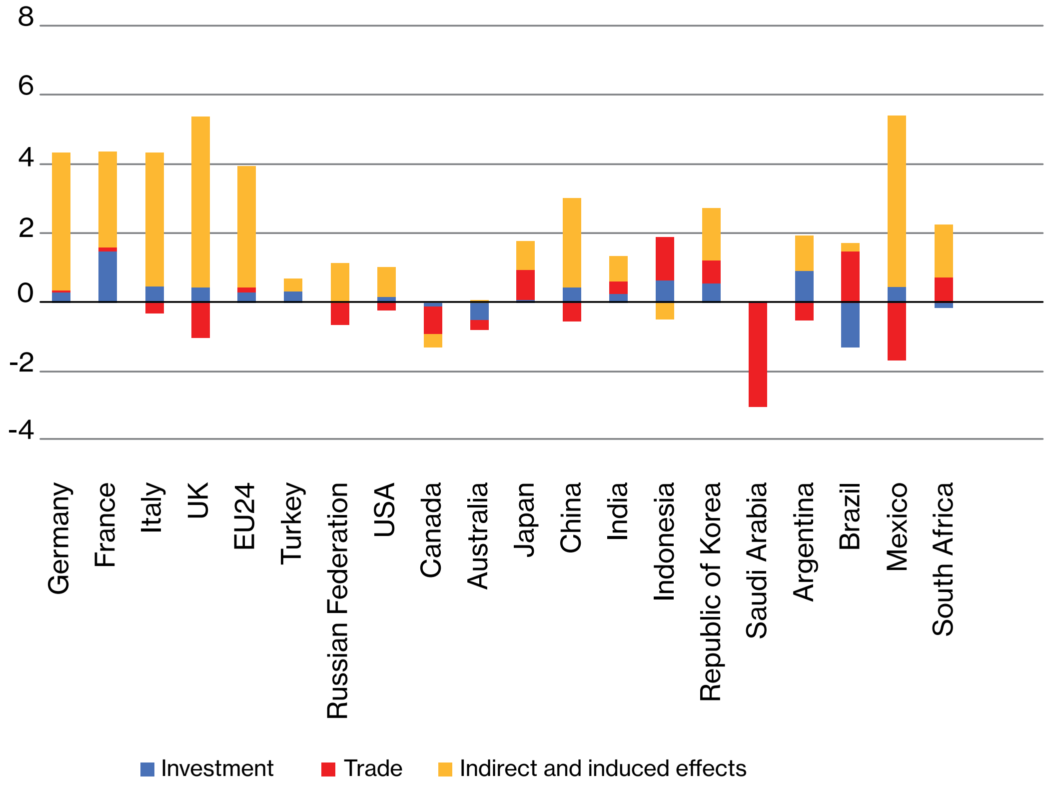


Figure 23. Dynamic evolution of the drivers for GDP creation from the Planned Energy Scenario and the Transforming Energy Scenario across the 2019 – 2050 period

Source. Data extracted from (IRENA, 2020b)

The drivers for GDP play very differently in the different G20 countries. To illustrate this point, Figure 26 presents the distribution of GDP drivers' impacts across the different G20 countries or regions in average terms during the 2019-2050 period, compared with the G20 aggregate. In the G20, the Transforming Energy Scenario produces (on average) a 2.4% GDP increase over the PES. That increase is strongly dominated by indirect and induced effects with a smaller positive contribution from investment and a negative but small contribution from trade. But the distribution within G20 is very unequal, both in overall GDP differences and in the weight from the different drivers. Some countries experience very favourable impacts, with about 5% increases in GDP in the Transforming Energy Scenario over the PES in Germany, France, Italy, UK and EU24. Other countries, such as Saudi Arabia, Canada and Australia, experience negative impacts. The indirect and induced effects driver dominates the positive results in many countries (Germany, France, Italy, UK, EU24, Russian Federation, USA, China, Republic of Korea, Mexico and South Africa), but has negative contributions in a few countries (Canada and Indonesia). Trade impacts tend to be negative in fossil fuel exporting countries and positive in fossil fuel importing countries. But other aspects, like the position in the fossil fuel cost-production curve and the global redistribution of trade in nonenergy sectors (influenced by the evolution of general prices in each country), also have relevant impacts. The investment driver tends to have a positive impact due to the investment stimulus in transition-related technologies; however in some countries (Australia and Brazil) foregone fossil fuel investment dominates.



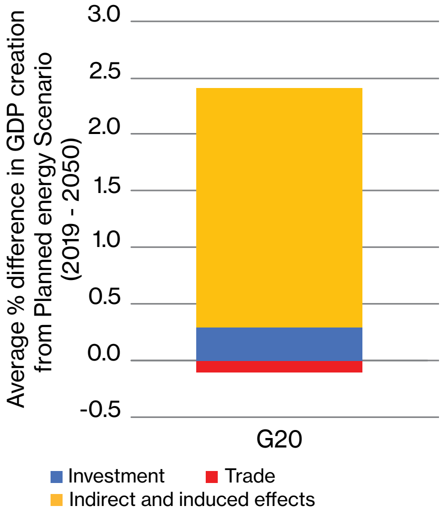


Figure 24. Average impact of the drivers for GDP creation from the Planned Energy Scenario and the Transforming Energy Scenario during the 2019-2050 period, and distribution of drivers' impacts within the G20
Source. Data extracted from (IRENA, 2020b)

In cumulative terms, the G20 difference in GDP between the Planned Energy Scenario and the Transforming Energy Scenario amounts to USD[2] 89 trillion, which in annualised and per capita terms (using the average population in the 2019-2050 period) is equivalent to USD 572/person/year. This value is significantly higher than the global result.

4.3 Welfare in the G20

The sections above discussed the employment implications of the energy transition. Beyond employment, other dimensions affect welfare. To capture a more holistic picture of the energy transition impact, IRENA uses a welfare index with three dimensions (economic, social and environmental) and two subdimensions in each.

Figure 25 presents the results of the welfare index for the G20 in the years 2030 and 2050. The welfare improvement of the Transforming Energy Scenario over the Planned Energy Scenario is very important, reaching 14% in 2050. Social and environmental dimensions, and specifically the health and GHG emissions subdimensions, dominate the overall welfare index results in the G20.

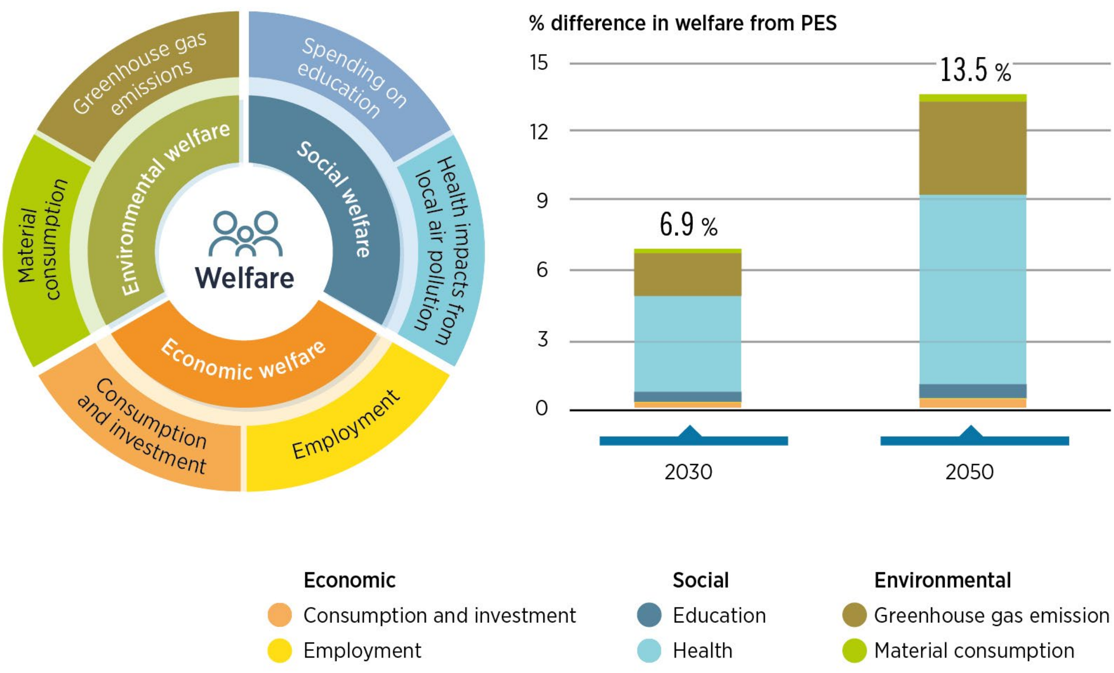


Figure 25. Evolution of the Welfare index for the G20 under the Transforming Energy Scenario
Source. Data extracted from (IRENA, 2020b)

05

Barriers to the deployment of renewable energy

Despite the powerful factors driving the global uptake of renewable energy, multiple barriers inhibit further uptake in developed and developing markets. These vary based on specific markets and renewable energy technologies. This section outlines the some of the main barriers globally.

Regulatory and policy barriers

Unfavourable, inconsistent, discontinuous or opaque policies can be significant barriers. Unclear support schemes or procedures lower confidence among investors and developers. Uncertainty and inconsistency about targets and policies, including retroactive changes, significantly hamper renewables expansion, as they lower the trust of investors.

Institutional and administrative barriers

These barriers include a lack of institutions and authorities dedicated to renewables, the absence of clearly defined responsibilities, complicated, slow, lengthy or opaque licensing procedures and inadequate planning guidelines. Institutional resistance to renewable energy can impede further development.

Cost barriers

Cost barriers pertain to the capital and investment costs of some renewable energy technologies compared with competing technologies in given contexts. Where sufficient resources exist, several renewable energy technologies are already cost-competitive compared with other fuels. While costs have fallen as deployment has accelerated across renewable energy technologies, higher costs remain for some, although effective cost-reduction opportunities do exist.

Financial barriers

The cost barrier is reinforced by the lack of adequate funding opportunities and financing products for renewables. Barriers include low availability and high cost of financing, difficulty of accessing suitable financial instruments, lack of institutional knowledge and lack of access to and affordability of effective risk mitigation instruments.

Market barriers

Inconsistent pricing structures, irregular pricing of renewable energy products, information asymmetries, distortions in market power, fossil fuel and nuclear subsidies, and a failure to incorporate social and environmental externalities into costs may lead to disadvantages for renewables. Many countries have energy tariffs that are not fully cost-reflective, as well as fossil fuel and/or nuclear subsidies that inhibit the deployment of renewables. Trade barriers in some countries – such as import duties – also make importing renewable energy products more expensive.

Lack of supporting infrastructure

The lack of facilities for transmission and distribution networks, equipment and services necessary for power companies is a major infrastructural challenge for renewable energy development, especially in developing countries. Beyond power, the progress of renewables for heating and cooling may be hindered by a lack of infrastructure, while efforts to decarbonise transport may be slowed by the absence of charging stations for EVs or appropriate engines in vehicle fleets for biofuels.

Grid integration challenges

The variability and uncertainty of solar PV and wind is a challenge on conventional grids, which were developed for large, centralised and dispatchable generators and largely variable and inflexible demand. The spread of renewable technologies requires many changes in the power grid structure to deal with variable generation and flexible demand. These challenges are amplified in situations with a weak grid, but can be addressed where the grid is expanding, as the grid can be updated as needed for the energy transformation.

Public acceptance and lack of awareness

The lack of adequate knowledge about renewables and their performance is a crucial barrier to the development of renewables. How end users perceive the complexity of technology and the costs involved have a large impact on their decisions about whether to embrace that technology or not. Lack of knowledge can reduce public acceptance, which can lead to higher costs, delays and even cancellation of projects (González, Ana María, Harrison Sandoval, Pilar Acosta and Felipe Henao, 2016)

Lack of capacity/skilled labour

The global shift to renewables requires skills – technical, business, administrative, economic and legal, among others. Lack of skilled personnel and training programs thus remains a barrier. Lack of know-how may also lead to improper usage and maintenance, which can create a negative perception and slow the adoption of renewables. This barrier is often greater in areas without access to energy.

06

Enabling policies

Countries need to be increasingly ambitious in their pledges to scale up renewables and cut energy-related carbon dioxide (CO_2) emissions.

Five years after the historic signing of the Paris Agreement, countries around the world are struggling to translate their emissions reduction pledges into concrete actions to fight climate change. IRENA estimates that if all national renewable energy targets in the first round of Nationally Determined Contributions (NDCs) are implemented, around 3.2 TW of renewable power capacity would be installed globally by 2030, 59% short of the capacity needed according to IRENA's Transforming Energy Scenario. In the G20, around 2.8 TW of renewable power capacity would be installed by 2030, 60% short of the 7 TW envisioned in the Transforming Energy Scenario (IRENA, 2019h). Considerable opportunity exists to raise ambitions in a cost-effective way through enhanced renewable energy targets.

Renewable energy targets have become key drivers of policies, investment and development, by providing clear indications of the intended deployment and timeline envisioned. However, national targets have focused on the power sector. At the end of 2019, 162 countries had targets for the power sector, compared to 47 countries with targets for heating and cooling and 45 for transport. Over 63% of power targets were already achieved at the end of 2018, leaving 866 GW of renewables yet to be installed globally. Over half of this – or 471.4 GW – is expected in the G20, with an estimated investment opportunity of USD 818 billion (IRENA, forthcoming a).

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 and long-term planning perspective. Long-term energy scenarios can support planning for a climate friendly energy system, and their boundaries need to be expanded beyond the power sector to also integrate traditional fuels, industrial processes and their economy-wide impacts.

Despite the remarkable progress made in the power sector, continuous adaption of policy instruments and market design is needed to achieve broader policy objectives and integrate higher shares of variable renewable energy into the system.

Widely adopted policy instruments such as auctions have reflected the rapidly falling technology costs and have delivered renewable electricity at competitive prices globally. By 2018, more than 106 countries had adopted auctions, owing chiefly to their ability to procure renewables-based electricity at the lowest price. The global average prices from solar PV auctions have decreased by 77%, and from onshore wind auctions by 36%, in the past decade. In 2018, solar energy was contracted at a global average price of almost USD 56/MWh, while wind average price was USD 48/MWh. G20 countries have been leading these trends (Figure 26), with record low prices achieved on many occasions in Brazil, Mexico and Saudi Arabia (IRENA, 2019i).

In addition to procuring renewable electricity cost-effectively, policy makers have pursued social and economic objectives through auctions. Auctions have been tailored to broader policy objectives, such as socio-economic benefits, including the inclusion of small and new players, job creation, subnational development and community benefits, and the development of local industries. South Africa was a pioneer in promoting economic development especially in underserved regions.

Innovative auction design has also helped address some of the challenges related to system integration with increasing shares of variable renewable energy (VRE) generation. Mexico has considered geographical allocation signals according to the network integration feasibility and costs. India and South Africa have sought to concentrate renewable project developments in specific geographical areas (IRENA, 2019i).

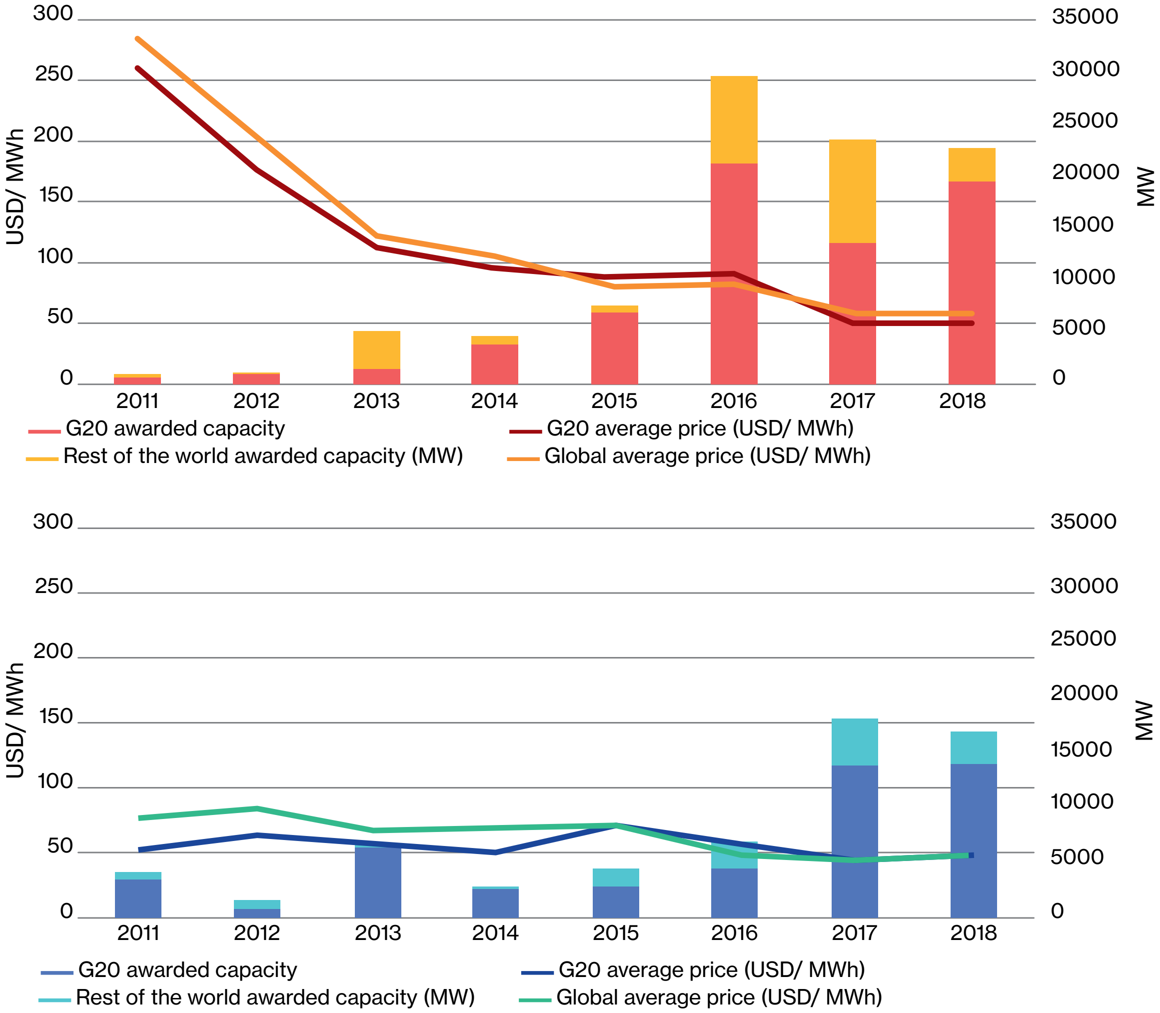


Figure 26. Weighted average prices of energy resulting from solar and wind auctions, globally and in G20 countries, and capacity awarded each year, 2011-2018

Source. Sources: (BNEF, 2019; IRENA, 2019i; PSR, 2019)

Measures to improve power system flexibility are needed to enable the integration of higher shares of VRE. Investment must be steered into innovations in all flexible resources (storage, demand-side management, interconnectors and dispatchable power plants), market design and system operations.

The new power system will have flexible demand and variable generation, and it would need a new and enabling power market design. In today's prevalent power systems, demand is inflexible and dispatchable generators cover variations in demand. As the power system evolves, a new power system structure will become necessary. The design should be focused on providing stable and long-term signals that reward VRE generation, but it should also offer economic incentives for the flexible operation that will be required. Regulations that govern the updated market design should allow the presence of new players and enhance cross-border trading of electricity (IRENA, 2020d).

Additional measures will be required to enable the electrifcation of end uses with renewables-based power.

Electrification with renewables calls for the synchronisation of the deployment of renewable power plants with sector coupling. In this regard, measures to deploy electricity-powered technologies in the transport and heating sectors should be adopted in a timely fashion. The private sector response to policy signals in the electrification of transport shows that such policy signals can be effective. Government interventions to support the deployment of heat pumps include investment subsidies, grants and tax exemptions and have been proved useful in stimulating the market (IRENA, IEA, REN21, 2018).

Electrification will increase electricity demand; appropriate measures have to be adopted to make electricity consumption system-friendly. In order to avoid grid congestion or recurrent scarcity events, incentives should be given to any power consumer to consume electricity in a system-friendly way. Price signals should be used to encourage consumers to use renewable energy, and time-of-use tariffs could help adjust demand to better meet solar and wind generation profiles.

Electrification will require strategies for the adoption of smart devices that unlock much more flexibility and control over demand and the delivery of renewable electricity. Digitalisation is critical to reduce the risk of rising peak loads and to expand opportunities for renewable power utilisation. Careful investment in the rollout of smart technologies can avoid the need for massive investment in building new grid infrastructure. Italy has been an early adopter of smart meters since 2006. This technology reduced distribution grid costs by 39% and decreased consumption peaks due to higher customer awareness and clear price signals (Gov.uk, 2017).

Policies and measures are needed to enable the transformation in heating and cooling and transport.

A climate-safe future calls for the scale-up and redirection of investment to renewable energy technologies and the infrastructure needed to support them. It will be necessary to redirect investments into solutions that can further reduce fossil fuel use, such as increased direct use of renewable energy, energy efficiency and supporting infrastructure. Redirecting investments will also need to be supported by the phase out of fossil fuel subsidies (IRENA, 2020b). In hard-to-abate sectors especially, fossil fuels have been the primary choice because of their energy density and relatively low prices due to direct and indirect subsidies, as their negative externalities are rarely accounted for.

Policies such as mandates and incentives, as well as fiscal policies, are needed to drive the decarbonisation of heating and cooling. Grants or tax incentives to subsidise the higher capital costs of renewable heat options are needed. Ambitious solar thermal targets, in addition to reduced system prices, were responsible for the impressive growth of solar water heaters in China (IRENA, forthcoming b) . In industry, co-generation with biomass has been incentivised by policies such as in India and Brazil, both of which have a large sugar industry and bagasse is frequently used in co-generation. (IRENA, forthcoming b)(IRENA, IEA, REN21, 2018)(IRENA, IEA, REN21, 2018)(IRENA, IEA, REN21, 2018).

Policy is also needed to direct investments into supporting the development of green hydrogen for industry and other hard-to-abate sectors. Hydrogen production is currently around 120 Mt per year, and dedicated hydrogen pipelines have been in operation for decades. However, 96% of all hydrogen today is produced from fossil fuels. Actions to be considered today include R&D policies to reduce the costs of hydrogen produced from renewable electricity, as well as new dedicated actions to create a green hydrogen market. Policy makers can enable green hydrogen by mandating clean and efficient energy use. Certification systems and regulations for carbon-free hydrogen supply are critical to ensure that any future hydrogen supply is climate-compatible, even when transported from distant places (IRENA, 2019j).

Policies and measures, in addition to structural changes and behavioural policies, will be needed to decarbonise the transport sector. Targets, fiscal and financial incentives, and investments in infrastructure, including charging stations, are crucial to support EVs, but these lead to renewable energy deployment only if they go hand in hand with renewables-based power generation. Blending mandates can be introduced to support biofuels, such as in European Union, Brazil, China and the United States. The reduction of traffic volume is one effective strategy for decarbonising transport. Policy makers can assist by promoting public transportation and other mobility services (e.g. carpooling), as well as measures to reduce avoidable trips, such as the promotion of home working. A reduction of traffic volume would ease the burden on both the power sector (for charging EVs) and biofuels.

For all end uses, 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, 2020b).

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.

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 from the energy transition, and they will face losses in the conventional energy sector to different degrees. Differences in regional socio-economic outcomes can be traced back to structural conditions, industrial capacities and trade patterns, and the depth and diversity of domestic supply chains.

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 (IRENA, 2020b).

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. Investments projected under the Transforming Energy Scenario would stimulate considerable job growth, most of it directly in renewables, where employment would rise to 42 million jobs by 2050. 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. Targeted education and capacity building policies must anticipate impending changes and nurture the diverse and growing labour force required by the transition (IRENA, 2020b).

International cooperation and solidarity are not only desirable, they are vital for addressing climate change, economic inequality and social injustice.

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 cooperation and solidarity are not only desirable, they are vital 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 (IRENA, 2020b).

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