

GLOBAL ENERGY TRANSFORMATION



A ROADMAP TO
2050

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About IRENA

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

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FOREWORD

The global energy transformation is happening, driven by the dual imperatives of limiting climate change and fostering sustainable growth. An unprecedented decline in renewable energy costs, new opportunities in energy efficiency, digitalisation, smart technologies and electrification solutions are some of the key enablers behind this trend.

At the same time, the energy transformation must happen much faster. To meet global climate objectives, the deployment of renewables must increase at least six-fold compared to current government plans. This would require the impressive progress that we are already witnessing in the power sector to accelerate even further, while efforts to decarbonise transport and heating would need to be stepped-up significantly.

Electrification is emerging as a key solution for reducing emissions but only if paired with clean electricity, which increasingly can be sourced at the lowest cost from renewable energy. The share of electricity in total energy use must increase to almost 50% by 2050, up from 20% today. Renewables would then make up two-thirds of energy consumption and 86% of power generation. Renewable electricity paired with deep electrification could reduce CO₂ emissions by 60%, representing the largest share of the reductions necessary in the energy sector.

Fortunately, this shift is also a path of opportunity. It would enable faster economic growth, create more jobs, and improve overall social welfare. Reducing human healthcare costs, environmental damages and subsidies would bring annual savings by 2050 of between three and seven times the additional annual costs of the transition. By 2050, the energy transformation would provide a 2.5% improvement in GDP and a 0.2% increase in global employment, compared to business as usual. However, climate damages will lead to significant socio-economic losses. Putting in place policies that ensure a just and fair transition will maximise the benefits for different countries, regions and communities as well as address inequalities. Transforming the global energy system will also enhance affordable and universal energy access and improve energy security.

While timely action would strand assets of over USD 7.7 trillion worth of energy infrastructure that is tied to today's polluting energy technologies, further delays would risk to significantly increase this amount.

The world's choices today will be crucial to reaching a sustainable energy and climate safe future. The Sustainable Development Goals and the Paris Agreement create the framework for the coordination and further acceleration of global efforts to advance the energy transformation.

The global pathway outlined in this report to achieve this needs to be matched by transformative action on the ground to ensure energy systems are fit for the renewable energy age, align energy policies with climate objectives, unlock investments, scale-up renewable energy projects, and strengthen local capacities. These priorities will be at the heart of IRENA's efforts in the period ahead, in working in partnership with the multilateral system, institutional and financial as well as engaging with the private sector, to support countries in their transition to a sustainable energy future.

I hope that this report provides a catalyst for high ambition matched with decisive action on the ground to advance an inclusive, fair and economically, socially and environmentally beneficial, energy transformation.



Francesco La Camera

Director-General, IRENA



THIS REPORT AND ITS FOCUS

In 2017, IRENA released its first report focused on long-term decarbonisation and on the technical feasibility and socio-economic benefits of a global energy transition (IEA and IRENA, 2017). In 2018 a second report was released (IRENA, 2018a), which expanded on the implications of the energy transition and detailed the global level of investment that is needed, while also providing a deeper view on key transition needs by sector and further insights into the socio-economic implications.

This 2019 edition updates IRENA's analysis of key countries and regions, and it presents a deepened perspective on electrification with renewable energy – the key enabling solution of the energy transition. The report also details new findings related to the costs, subsidies and investments needed for the transition. IRENA's socio-economic footprint analysis delves into the implications of the transition, providing footprint measurement in terms of GDP, jobs and welfare. A discussion of the socio-economic implications of carbon taxation is presented. Climate damages have been included into the macroeconomic analysis, bringing about important socio-economic consequences. The need for holistic employment and just transition policies is highlighted by analyzing the implications of the transition on whole-economy and energy sector jobs. The focus also has been strengthened on how high shares of variable renewable energy (VRE) can be integrated into energy systems. In addition to discussion on the role of electrification, solutions for decarbonising heating, cooling and transport demand are also presented.

THIS REPORT FOCUSES ITS ANALYSIS ON TWO PATHWAYS FOR THE GLOBAL ENERGY SYSTEM:

Reference Case

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

REmap Case

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

This report also benefits from other work-streams within IRENA and incorporates inputs and recommendations from the following underlying studies and analyses:

Innovation landscape for a renewable-powered future (IRENA, 2019b) – This report provides solutions to integrate variable renewables. It explains how innovations in technology, market design, business models and system operation are being combined to create solutions suitable for a wide range of power systems and provides a clear framework to support decision making. It is complemented by 30 innovation briefs.

Electrification with renewables (IRENA, 2019c) – This report analyses the need for a vast expansion of renewables, for smarter and more flexible electricity grids, and for increases in the numbers of vehicles and other products and processes that run on electricity.

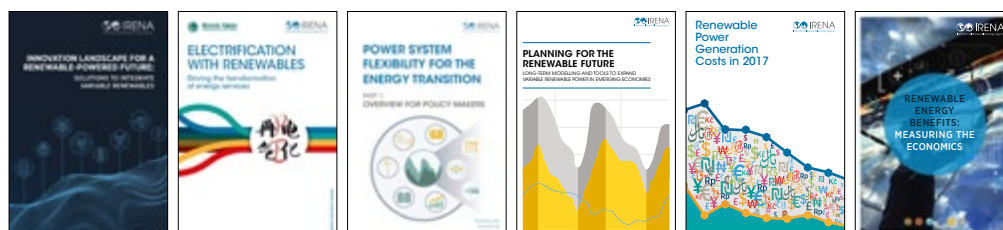
A new world: The geopolitics of the energy transformation (IRENA, 2019d) – This report analyses the geopolitical implications of the global energy transformation driven by renewables. It is the culmination of 10 months of deliberations by the Global Commission on the Geopolitics of Energy Transformation.

Power system flexibility for the energy transition (IRENA, 2018b, 2018c) – In this study, IRENA's FlexTool, methodology and case studies are used to explore technical solutions to boost power system flexibility to accommodate high shares of VRE, including stronger transmission and distribution systems, storage capacity, demand-side management, etc.,

Planning for the renewable future: Long-term modelling and tools to expand variable renewable power in emerging economies (IRENA, 2017a) – This report informs decision makers, energy planners and technical practitioners by providing an overview of key long-term issues and concerns around the large-scale integration of variable renewables into the power grid, specifically with a catalogue of practical modelling methodologies for VRE for long-term scenario planning.

Cost analysis (IRENA, 2018d) – The IRENA Renewable Cost Database is the world's largest dataset on power generation projects, power purchase agreements and tender results.¹ The database provides new insights into trends in the costs and performance of renewables. It includes data on 1 334 gigawatts (GW) of projects and 393 GW of auction data. It covers around half of all renewable capacity added to 2017 and a large share of new capacity added worldwide (e.g., 59% of new capacity additions in 2017).

Socio-economic benefits of renewable energy deployment – This collection of reports highlights numerous socio-economic benefits of renewable energy developments, including economic growth, job creation, access to energy, human health improvement and overall welfare enhancement.²



¹ For more information on IRENA's cost database, please visit <https://www.irena.org/costs>.

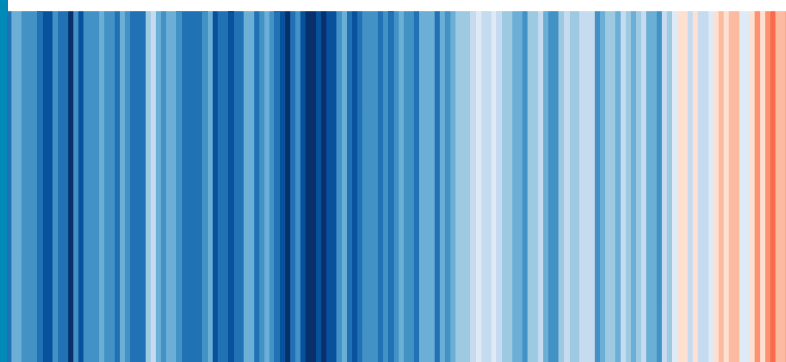
² Socio-economic series of publications are available at https://www.irena.org/publications/Our-Collections#Socio_Economic_Benefits.

ABBREVIATIONS

°C	degrees Celsius
bcm	billion cubic metres
bln	billion
CCS	carbon capture and storage
CO ₂	carbon dioxide
CSP	Concentrated Solar Power
DH	district heat
EJ	exajoule
EV	electric vehicle
G20	Group of Twenty
GDP	gross domestic product
GJ	gigajoule
Gt	gigatonne
GW	gigawatt
GWh	gigawatt-hour
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
kWh	kilowatt-hour
LCOE	levelised cost of energy
m ²	square metre
mIn	million
Mt	megatonne
Mtce	megatonne of coal equivalent
Mtoe	million tonnes of oil equivalent
MW	megawatt
MWh	megawatt-hour
NDC	Nationally Determined Contribution
OECD	Organisation for Economic Co-operation and Development
ppt	percentage point
PV	photovoltaic
REmap	renewable energy roadmap analysis by IRENA
SDG	Sustainable Development Goal
t	tonne
TFEC	total final energy consumption
toe	tonne of oil equivalent
TPES	total primary energy supply
TWh	terawatt-hour
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
US	United States of America
USD	United States dollar
VRE	variable renewable energy
WMO	World Meteorological Organization
yr	year

Annual global temperatures from 1850-2017

Warming Stripes, by **Ed Hawkins**, climate scientist in the National Centre for Atmospheric Science (NCAS) at the University of Reading.



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

CONTENTS

THIS REPORT AND ITS FOCUS.....	4
HIGHLIGHTS FROM THIS YEAR'S REPORT.....	8
KEY FINDINGS	10
REPORT	15
Mixed progress on the energy transition	15
A pathway for the transformation of the global energy landscape.....	19
Measuring the socio-economic footprint of the energy transition	35
Action needed now	45
REFERENCES	50

FIGURES

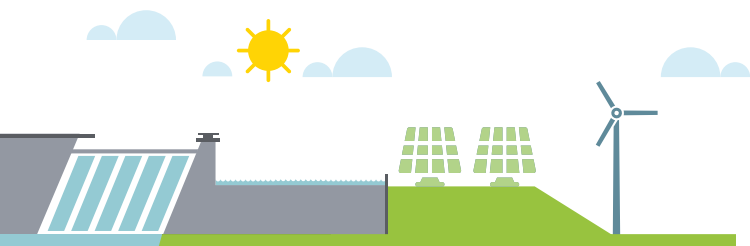
Figure 1. Key milestones over the past 20 years in renewables and digitalisation	17	Figure 12. Renewable energy share and energy demand projections for key scenarios... ..	34
Figure 2. A roadmap to 2050	20	Figure 13. The global transformation of the energy system offers socio-economic benefits	35
Figure 3. REmap offers a pathway for a well-below 2°C climate target, towards 1.5°C	22	Figure 14. Implementation of sector-level actions from now is highly essential to effectively transform the global energy system	36
Figure 4. Renewables and energy efficiency, boosted by substantial electrification, can provide over 90% of the necessary reductions in energy-related carbon emissions	23	Figure 15. Relative difference of global GDP between the REmap Case and the Reference Case, 2019-2050.....	37
Figure 5. Renewables share in total final end-use consumption needs to accelerate six-fold compared to current levels.....	25	Figure 16. Relative difference of global employment between the REmap Case and the Reference Case, 2019-2050.....	39
Figure 6. Energy intensity improvements broken down into higher electrification of end-use applications, renewable energy deployments and energy efficiency.....	26	Figure 17. Impact of climate damages on the GDP indicator used for the socio-economic footprint analysis	41
Figure 7. Scaling up renewables not just for power, but also for heat and transport	27	Figure 18. Impact of climate damages on GDP results..	42
Figure 8. Electricity becomes the main energy source by 2050	29	Figure 19. Implementation of sector-level actions from now is highly essential to effectively transform the global energy system.....	48
Figure 9. Wind and solar power dominate growth in renewable-based generation.....	30		
Figure 10. Shifting investment to energy efficiency, renewables and the electrification of heat and transport	31		
Figure 11. Benefits of the energy transformation compared to expenditures	33		

BOXES

Box 1. Climate change is accelerating	19
Box 2. Evaluating the impact of climate damages in the macroeconomic performance.....	43
Box 3. What does the applied climate damage methodology include and what not? ...	44

HIGHLIGHTS

- **ELECTRIFICATION WITH RENEWABLE POWER** can start to reduce energy-related carbon dioxide (CO₂) emissions immediately and substantially. The pairing is also getting cheaper than fossil fuel-based alternatives, lowers local air pollution and increases health benefits, results in positive socio-economic benefits and will be a key enabler to build a connected and digitalised economy and society. Electrification, when paired with renewables, goes hand-in-hand with energy efficiency, resulting in lower overall energy demand.
- By 2050 **ELECTRICITY** could become the central energy carrier, growing from a 20% share of final consumption to an almost 50% share – and, as a result, gross electricity consumption would more than double. Renewable power will be able to provide the bulk of global power demand (86%). The primary drivers for this increased electricity demand would be over 1 billion electric vehicles, increased use of electricity for heat and the emergence of renewable hydrogen. Overall, renewable energy would supply two-thirds of final energy.
- For every USD 1 spent for the energy transition, there would be a **PAYOFF** of between USD 3 and USD 7 – or, put in cumulative terms over the period to 2050, a payoff of between USD 65 trillion and USD 160 trillion. The energy transition requires fewer overall subsidies, as total energy sector subsidies can be reduced by USD 10 trillion over the period. The focus of subsidies will need to change progressively, however – away from power and fossil fuels and into energy efficiency technologies and solutions needed to decarbonise the industry and transport sectors.
- The level of **ADDITIONAL INVESTMENTS** needed to set the world on a more climate-friendly path above current plans and policies is USD 15 trillion by 2050 – a significant sum, but one that decreased by over 40% compared to the previous analysis due in large part to rapidly falling renewable energy costs as well as opportunities to electrify transport and other end-uses. Overall, total investment in the energy system would need to reach USD 110 trillion by 2050, or around 2% of average annual gross domestic product (GDP) over the period.



- Annual **ENERGY-RELATED CO₂ EMISSIONS** in the REmap Case decline 70% below today's level. An estimated 75% of this reduction can be achieved through renewable energy and electrification technologies; if energy efficiency is included, then this share rises to over 90%. However, the world is on a much different path: energy-related emissions have risen by over 1% annually, on average, over the last five years. Current plans and policies, including Nationally Determined Contributions (NDCs), result in a similar level of annual emissions in 2050 compared to today, which risks putting the world on a pathway of 2.6 degrees Celsius of temperature rise or higher already after 2050. The report shows that emissions would need to be reduced by around 3.5% per year from now until 2050, with continued reductions after that time. Energy-related emissions would need to peak in 2020 and decline thereafter.
- Any energy transition roadmap will interact with the evolution of the socio-economic system upon which it is deployed, producing a series of outcomes that can be understood as the **SOCIO-ECONOMIC FOOTPRINT**. The degree to which this footprint includes benefits or less favourable outcomes depends on the synergies between the energy transformation and the evolution of the socio-economic system. The balance between benefits and less favourable outcomes varies by region due to their diverging transformation ambition and different socio-economic dynamics.
- The energy transformation roadmap **IMPROVES THE SOCIO-ECONOMIC FOOTPRINT** over the Reference Case globally. By 2050, GDP increases by 2.5%, relative to the Reference Case. In terms of economy-wide employment, the gain over the Reference Case is 0.2%. However, within the energy sector itself, the loss of fossil fuel-related jobs is more than compensated by the increase in transition-related employment (renewables, energy efficiency, and energy flexibility). The overall relative improvement over the Reference Case across the three dimensions of the welfare indicator (economic, social and environmental) is 17%, strongly driven by the improvements in health and environment.
- **CLIMATE DAMAGES** significantly reduce the macroeconomic performance of both the Reference and REmap cases, with the impact increasing over time as climate change unfolds, making from increased transition ambition a priority goal. Due to the emissions mitigation of the REmap energy transformation, climate damages on the overall economy are lower than on the Reference Case, and hence the relative performance over the Reference Case improves. In terms of GDP, by 2050, the relative improvement over the Reference Case increases from 2.5% to 5.3% when climate damages are factored into the macroeconomic analysis.
- **TECHNOLOGY** is progressing rapidly, and solutions exist today that are deployable at large scale and are increasingly cost-competitive. Governments are lagging and should implement more aggressive climate, renewable energy and energy efficiency policies and targets. Importantly, they should align climate and sustainability targets with energy plans, and they should value these plans beyond just the effect on the energy sector and take a more holistic, socio-economic view. The Sustainable Development Goals, and the revisions of NDCs, provide an opportunity for governments to work regionally and internationally to drive co-ordinated action.
- **SYSTEMIC INNOVATION** is crucial as a key enabler for the energy transition. Countries need to devote more attention to enabling smarter energy systems through digitalisation, through the coupling of sectors via greater electrification, and by embracing decentralisation trends. This innovation also needs to be expanded beyond technology and into markets and regulations as well as new operational practices in the power sector and business models.

KEY FINDINGS

The transformation of the global energy system needs to accelerate substantially to meet the objectives of the Paris Agreement. Those objectives are to keep the rise in average global temperatures “well below” 2 degrees Celsius (2°C) and ideally to limit warming to 1.5°C in the present century, compared to pre-industrial levels.

- Despite clear evidence of human-caused climate change, support for the Paris Agreement on climate change, and the prevalence of clean, economical and sustainable energy options, **energy-related carbon dioxide (CO₂) emissions have increased 1.3% annually, on average, over the last five years.** The gap between observed emissions and the reductions that are needed to meet internationally agreed climate objectives is widening.
- In the last few years the **energy sector has started changing in promising ways.** Renewable power technologies are dominating the global market for new generation capacity, the electrification of transport is showing early signs of disruptive acceleration, and key enabling technologies such as batteries are experiencing rapid reductions in costs.
- Despite these positive developments, **deployment of renewable solutions** in energy-consuming sectors, particularly buildings and industry, **is still well below the levels needed, and progress in energy efficiency is lagging.**
- **Structural change also plays a critical role in meeting global climate targets and enabling the high level of energy efficiency that is required.** Changes include modal shifts in transport (e.g., from individual passenger cars to shared mobility and public transport), as well as efforts in industry such as the circular economy and industry relocation to areas where renewable energy is plentiful.
- **Investment in infrastructure needs to be focused on low-carbon, sustainable and long-term solutions that embrace electrification and decentralisation.** Investment is needed in smart energy systems, power grids, recharging infrastructure, storage, hydrogen, and district heating and cooling in cities.
- **Circular economy practices can drive aggressive, and readily realisable, reductions in energy demand and emissions.** Reusing, recycling and reducing the use of water, metals, resources, residues and raw materials in general should be amplified. Lifestyle changes can facilitate deeper emissions reductions which are challenging to implement and accurately forecast over decades.

Renewable energy supply, increased electrification of energy services, and energy efficiency can deliver more than 90% of needed reductions to energy-related CO₂ emissions. Renewable energy and electrification alone deliver 75% of emission reductions.

- **The share of renewable energy in primary energy supply would grow from less than one-sixth today to nearly two-thirds in 2050 in the REmap Case.**
- Energy efficiency must be scaled up substantially; **the rate of energy intensity improvement would increase to 3.2% per year**, up from recent historical averages of around 2.0% per year.
- **Electricity would progressively become the central energy carrier, growing from a 20% share of final consumption to an almost 50% share by 2050**, and renewable power would be able to provide the bulk of global power demand (86%) economically. As a result gross electricity consumption would more than double.
- The transition to increasingly **electrified forms of transport and heat**, when combined with the increases in **renewable power** generation, **can deliver around 60% of the energy-related CO₂ emissions reductions needed** to set the world on a pathway to meeting the Paris Agreement. When these measures are combined with direct use of renewable energy, the share of the emissions reductions from these combined sources reaches 75% of the total required.
- However, emissions will still need to be reduced further, and **bioenergy will play a role in sectors that are hard to electrify, such as shipping, aviation and certain industrial processes**. Biofuel consumption must be scaled up sustainably to meet this demand. Efforts also are needed to reduce non-CO₂ greenhouse gas emissions and non-energy use emissions (such as by using waste-to-energy, bioenergy and hydrogen feedstocks); to reduce industrial process emissions; and to reduce fugitive emissions in the coal, oil and gas industries. Efforts are needed outside of the energy sector to reduce greenhouse gas emissions in agriculture and forestry.

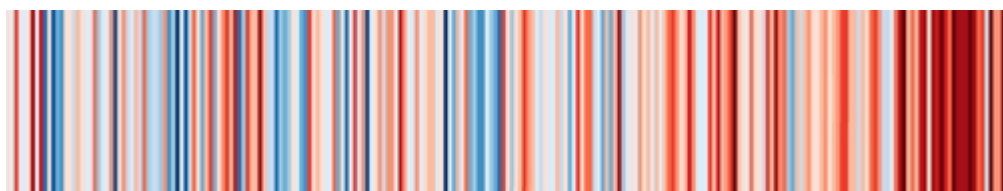
The global energy transformation makes economic sense.

- According to current and planned policies, the global energy sector will see cumulative investments of USD 95 trillion over the period until 2050. **The transition towards a decarbonised global energy system will require scaling up investments in the energy sector by a further 16% (an additional USD 15 trillion by 2050). In total USD 110 trillion would be invested in the energy system**, representing on average 2% of global gross domestic product (GDP) per year over the period.
- **The types of investments will change, with a shift in the composition of investments away from the fossil fuel sector towards energy efficiency, renewables and enabling infrastructure**. Crucially, the additional investments that are required are 40% lower than was estimated in the previous analysis (IRENA, 2018a), due largely to rapidly falling renewable power costs and the potential for further cost reductions, as well as the emergence of electrification solutions that are getting cheaper and more efficient.

- **The additional investments needs are, however, front loaded.** While additional investments are required in the first period of the transition (to 2030), as the year 2050 approaches, technology progress, better understanding of the power system and increasing electrification of end-use applications result in more optimistic, lower investment estimates.
- Energy sector subsidies totalled at least USD 605 billion in 2015 and are projected to increase to over USD 850 billion annually by 2050 in the Reference Case. In contrast the REmap Case would result in a decline in subsidies to USD 470 billion in 2050. The types of subsidies would change drastically, moving away from fossil fuels and renewable power technologies to technologies needed to decarbonise the transport and industry sectors. **The REmap Case would result in a cumulative reduction in fossil fuel subsidies of USD 15 trillion below what would have occurred in the Reference Case by 2050, and in a net reduction of USD 10 trillion when including the increased support needed for renewables in the REmap Case.**
- **In total the savings from avoided subsidies and reduced environmental and health damages are about three to seven times larger than the additional energy system costs.** In monetary terms, total savings resulting from the REmap Case could amount to between USD 65 trillion and USD 160 trillion over the period to 2050. **Viewed differently, for every USD 1 spent, the payoff would be between USD 3 and USD 7.**

The socio-economic footprint of the energy transformation measures the net result of the multiple interactions between the energy transformation and the socio-economic system.

- **The energy transition cannot be considered in isolation from the broader socio-economic system.** For the transition to renewable sources and technologies to succeed, policies must be based on a more integrated assessment of the interactions between the evolving energy sector and the wider economy.
- Changes in the energy system have impacts throughout the economy. Globally, **the transition promises GDP, job creation and human welfare benefits.** By year 2050, the REmap energy transition brings about relative improvements of GDP and whole-economy employment of 2.5% and 0.2% respectively. In cumulative terms from 2019 to 2050 the GDP gains of the REmap Case over the Reference Case add up to 99 USD trillion. **The global welfare indicator measuring the improvement of REmap over the Reference Case reaches in 2050 a value of 17%.**
- As is the case with any economic transition, some regions and countries will fare better than others. **Regions with high dependence on fossil fuel exports and/or weak, non-diversified domestic supply chains face an adjustment challenge.** Failure to address distributional aspects can also introduce significant transition barriers.



Annual temperatures in central England from 1772-2017

The colour scale goes from 7.6°C (dark blue) to 10.8°C (dark red)

Source: <http://www.climate-lab-book.ac.uk/2018/warming-stripes/>

The socio-economic footprint of the energy transformation is shaped in significant ways by the policy framework

- **Besides the energy transformation characteristics** (energy balances and investments), **many other policy inputs can have an important impact on the socio-economic footprint**. Carbon taxes and fossil fuel subsidies are among these policy inputs.
- **Carbon taxes** on the level required for a 2°C global warming climate goal **can have a significant socio-economic impact**, which will be positive or negative depending on the policy framework that accompanies the deployment of carbon taxes. Special care needs to be taken concerning the distributional impacts of carbon taxes, both within and between countries, with **policy frameworks aiming at reducing inequalities** becoming important energy transformation enablers.

- Across the world economy, overall employment increases between 2018 and 2050 for both the Reference and REmap cases, with CAGRⁱ of 0.45% and 0.46% respectively. **The REmap Case produces more jobs than the Reference Case**, with relative gains peaking around 2035 and remaining around 0.2% until 2050.

A holistic employment policy is required for the energy transformation to have positive contributions in this welfare dimension

- The employment impact of the REmap transition in the energy sector is very positive, with **new jobs associated with the transition (i.e., renewable generation, energy efficiency and energy flexibility) significantly outweighing the jobs lost in the fossil fuel sector**. Since the energy-related jobs are significantly increasing while the number of jobs in the overall economy are barely increasing over the Reference Case (0.2% relative increase in 2050), jobs in non-energy related sectors are declining in relative terms to the Reference Case - partly due to the crowding-out effect.
- **The geographic and temporal distribution of energy sector jobs gained and lost is unlikely to be well-aligned, while jobs in other sectors of the economy could decline**. This calls for widening the conceptual framework to include just transition considerations and clearly requires addressing temporal, spatial and educational mismatches between new jobs and job losses throughout the economy. Therefore, **specific policies will be needed to address these mismatches to ensure that transition outcomes are just both in the energy sector and beyond**.

ⁱ CAGR stands for the Compound Annual Growth Rate. The CAGR is measure of growth over multiple time periods. It can be thought of as the growth rate that gets you from the initial GDP value to the ending GDP value if you assume that the GDP has been growing over the time period with a constant annual growth rate equal to the CAGR

Climate damages will have a significant impact on the socio-economic footprint

- It should be noted that **the main socio-economic results presented (GDP and jobs) do not capture the impacts of climate change**, the very driver of the energy transition on the economy. The macroeconomic model assumes that economic activity is not influenced by climate change, and hence both the Reference and REmap cases are left to progress along their macroeconomic pathways. IRENA has made a first attempt to quantify the impacts of climate damage on GDP.
- **IRENA has been working to include the impact of climate damages into its macroeconomic modelling.** However, the approach has to be understood as conservative because it does not include many of the potential impacts of climate change into the economy.
- Climate damage impacts increase with time as the climate system responds to the cumulative GHG emissions. **Macroeconomic performance under both the Reference and REmap cases is significantly impacted by climate damages, leading to a global GDP reduction of 15.5% and 13.2%, respectively, by 2050.** Despite this high impact, the global economy would still experience a significant growth due to the high growth rates achieved without climate damages under the considered socio-economic context: The CAGR between 2019 and 2050 with climate damages would be 1.8% and 2.0% for the Reference and REmap cases respectively, down from the 2.4% and 2.5% without climate damages.
- When comparing the relative GDP performance of the REmap over the Reference case, since climate damages have more impact in the Reference Case than in the REmap Case due to the CO₂ mitigation associated with REmap, a significant improvement is obtained when climate damages are factored into the analysis: **by 2050 the incorporation of climate damages leads to an increase of the $(GDP_{REmap} - GDP_{Reference}) / GDP_{Reference}$ socio-economic footprint indicator from 2.5% to 5.3%.**

Improving the transition's socio-economic footprint

- Modifying the socio-economic structure **incorporating fair and just transition elements improves the socio-economic footprint and prevents barriers** that could ultimately halt the transition.
- **The socio-economic footprint can be substantially improved through greater ambition in all countries and regions.** This would reap the benefit of minimizing climate damages, while the associated investment stimulus can produce important socio-economic benefits.
- **Negative impacts on low-income countries must be addressed for the transition to be successful** (e.g., ensuring adequate financing; addressing the distributional impacts of transition policies with justice and equity criteria; reinforcing domestic supply chains to reap indirect and induced effects from the transition).



REPORT

The global energy transformation is picking up pace. While steps have been taken in recent years in the right direction, a greater acceleration is needed that is centred on renewable energy, electrification and energy efficiency. This report outlines that transformation. Such a global energy transformation – seen as the culmination of the “energy transition” that is already happening in many countries – can create a world that is more prosperous and inclusive. It is, however, more than a simple transformation of the energy sector – it is a transformation of economies that would bring new opportunities and greater prosperity while also improving the air quality in our cities, preserving the environment and protecting our climate; but it will also be a complex transformation that will deeply affect economies and societies.

This report is based on the International Renewable Energy Agency (IRENA) Renewable Energy Roadmap (REmap) and on the socio-economic pathway analysis. It outlines an aggressive, yet feasible, course for the global energy transition. The report brings new insights. For instance, it shows that the outlook for energy-related carbon dioxide (CO₂) emissions in the Reference Case has improved compared to the previous analysis, but that emissions in recent years have risen, not declined as one would expect. The report also presents new findings on the costs, subsidies and socio-economic effects of the transition. Finally, it provides new insights on the crucial role of renewable power and electrification technologies and identifies them as the key enablers for energy-related CO₂ emissions reductions.

MIXED PROGRESS ON THE ENERGY TRANSITION

Positive steps

Technology has already transformed a wide array of sectors, and is now greatly disrupting the energy sector. The confluence of smart energy networks, digital solutions that better allow for controlling energy demand and trade, electrification and ample, low-cost renewable power has the potential to transform the energy sector in a way that just a few years ago seemed improbable. Developments are already being seen in several key areas. Yet the transition cannot be achieved through technology advancement alone. Policies are needed to better align international energy and climate plans, and countries need to increase their levels of emissions reduction ambition.

Costs of renewable energy have continued to decline rapidly. Overall the fall in electricity costs from utility-scale solar photovoltaic (PV) projects since 2010 has been remarkable, with the global average cost

declining 73% (IRENA, 2018d). Cost declines have been seen in diverse countries ranging from Saudi Arabia and the United Arab Emirates to Brazil and the United States (US), where wind and solar PV costs are now approaching 2-3 US cents per kilowatt-hour (kWh) (CleanTechnica, 2018; GTM, 2019; IRENA, 2018d). In Europe, offshore wind can now compete at market prices. In the US, the Energy Information Administration expects non-hydroelectric renewable energy resources such as solar and wind to be the fastest growing source of electricity generation nationwide in 2019 and 2020 (EIA, 2019).

Large economies are increasingly powered by renewables. Renewables are projected to have produced 33% of total power generation in the United Kingdom and 40% of total power generation in Germany and Spain in 2018 (Energy Reporters, 2018; FT, 2019a; PV Magazine, 2019), and instantaneous

generation can reach even higher levels. China reached a 38% share of renewable generation capacity at the end of 2018, and at the same time was able to greatly reduce the amount of power that was unusable and wasted due to grid flexibility issues (a phenomenon known as “curtailment”) (Reuters, 2019). Progress is also being seen elsewhere: Chile is undergoing a renewable energy boom and for the last few years has been one of the largest renewables markets in Latin America (PV-Tech, 2018), and Morocco is pioneering its own boom, with renewable power providing 35% of its electricity in 2018 (MoroccoWorldNews, 2019).

Wind and solar power dominated overall renewable energy additions in the power sector again in 2018, with an estimated 51 gigawatts (GW) of wind power (GWEC, 2019) and 109 GW of solar PV power (BNEF, 2019) installed. For the seventh successive year, the net additional power generation capacity of renewable sources exceeded that of non-renewable sources. Growth rates in renewable power have averaged 8-9% per year since 2010 (IEA, 2018a).

Global electricity markets are constantly evolving to meet the growing demand for renewable energy required by different types of consumers, including companies. IRENA estimates that at the end of 2017, the global corporate renewable electricity market reached 465 terawatt-hours (TWh) (comparable to the consumption of France today), representing approximately 3.5% of total electricity demand and 18.5% of the renewable electricity demand in the commercial and industrial sector (IRENA, 2018e).

Expanding the use of electricity is the main driver for accelerating the energy transformation. In particular, the electric mobility revolution is gaining pace. Electric vehicle (EV) sales (both battery-electric and plug-in hybrids) surpassed 2 million units in 2018, a 58% growth over the previous year (InsideEVs, 2019). In Norway, EV sales grew 40% in 2018, with nearly half of all passenger cars sold being electric that year (Electrek, 2019). Globally, around 5.6 million battery-electric light vehicles were on the road by the end of 2018 (EV Volumes, 2018). The switch to electricity is not just happening with cars. Electric buses are making large in-roads, particularly in China, where some cities have converted their entire public bus fleet to electricity. For instance, Shenzhen has over 16 000 electric buses in operation (The Guardian, 2018).

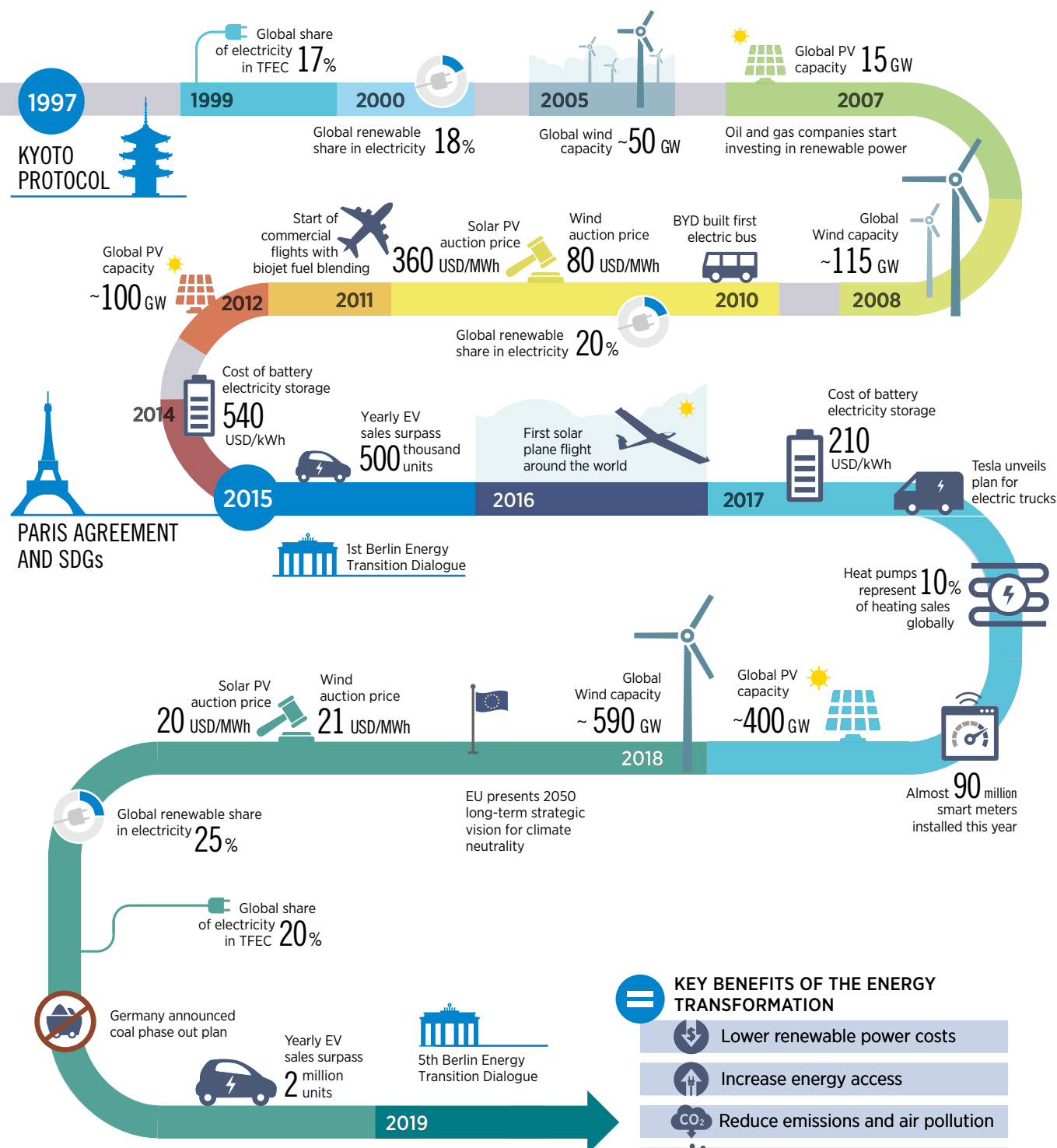
While electricity is clearly making in-roads in transport, steps are also being taken to electrify heat. In some

Nordic countries, heat pumps now account for more than 90% of the sales of space heating equipment (EHPA, 2017). Countries also are exploring the use of heat pumps and electric boilers with storage for their district heating systems. Denmark, for example, announced plans in 2018 to set up 13 large district heat-pump projects across the country in order to reduce emissions from its heat networks.

The aviation sector will need to address its rising emissions if the world is to meet climate targets. If it were a country, this sector would represent the eighth largest emitter of CO₂, and it is the mode of transport that is experiencing some of the largest growth in emissions. Many airlines, manufacturers and industry associations have committed to voluntary, aspirational targets that would collectively achieve carbon-neutral growth by 2020 and a 50% reduction in greenhouse gas emissions by 2050 (relative to 2005 levels) (IRENA, 2017b).

Emissions in aviation could be reduced by around 1.5% annually through improved fuel efficiency, new aircraft, modifications to aircraft and optimised navigational systems. However, there is a need to further reduce emissions through the use of advanced biofuels, namely biokerosene, or “biojet”. In the last few years numerous tests have been conducted of airplanes flying routes fuelled with biojet, proving that the technology is feasible, but it requires further commercialisation and improvement in costs. The regulatory framework for transport biofuels has been uncertain, and investment activity has consequently been stagnant for the last decade. Visibility regarding future markets has been poor and changes have been frequent, hampering investment.

Finally, while it appears that coal use may have increased slightly in 2018, coal consumption has been declining year on year for the last few years, and there is an increasing trend by countries, corporations, traders and investors to shy away from coal investment (IEA, 2018b). Meanwhile, renewable energy investment continues, albeit slightly lower than in 2017, with Bloomberg New Energy Finance estimating total investments at USD 332 billion in 2018 (BNEF, 2019). There are also signs that even the oil majors are considering getting more into the electricity business. Royal Dutch Shell recently said it could develop a power business and mentioned that it could become one of the largest electricity companies globally by 2030 (FT, 2019b).

Figure 1. Recent progress of the energy transformation*Key milestones over the past 20 years in renewables and digitalisation***KEY BENEFITS OF THE ENERGY TRANSFORMATION**

- Lower renewable power costs
- Increase energy access
- Reduce emissions and air pollution
- Increase welfare and growth

Sources: (IEA, 2018c); (IRENA, 2018f); (GWEC, 2015); (Reuters, 2007); (IRENA, 2018d); (INSIDEEVs, 2019b); (IEA-PVPS, 2018); (EV Volumes, 2019); (Solar Impulse, 2019); (IRENA, 2017c); (Electrek, 2017); (IEA, 2019); (GlobalData, 2018); (EC, 2018a); (GWEC, 2019); (CleanTechnica, 2018); (IATA, 2018); (BNEF, 2018).

The implications of climate change and the potential of the energy transition have yet to be fully grasped

The gap between aspiration and reality in tackling climate change remains significant, as highlighted by the Intergovernmental Panel on Climate Change (IPCC) special report on the impacts of global warming of 1.5 °C (IPCC, 2018). Rising CO₂ emissions, an uneven distribution of efforts among countries and short-sighted fossil fuel investments all increase the risks of the world going further off course. The urgency of action to combat climate change – and the impacts of the policies needed to get the world back on track – need to be fully grasped by decision makers, consumers and businesses. This report shows that global fossil fuel production under current and planned policies of the Reference Case will peak between 2030 and 2035; whereas for a pathway aligned with the Paris Agreement goals, the peak would need to occur in 2020.

If governments' long-term plans, including their Nationally Determined Contributions (NDCs), were followed, annual energy-related CO₂ emissions will decline only slightly by 2050, and will put the world on track for at least 2.6 °C of warming after 2050. In 2017 and 2018 energy-related CO₂ emissions rose, driven largely by increased use of fossil fuels; on average, energy-related CO₂ emissions have risen around 1.3% annually over the last five years (Carbon Brief, 2018).

In many countries, energy policies are not sufficiently aligned with climate goals, and policies often lag market developments. The energy transition also has been closely linked with the United Nations' Sustainable Development Goals (SDGs) and needs to be viewed within the larger framework of economic development and sustainability. It is also clear that a politically viable transition must be fair and just for it to succeed on a global level.

An energy transition will have significant geopolitical implications, as it will bring about power shifts in the relative position of countries, change energy trade balances and impact renewable energy supply chains. The Global Commission on the Geopolitics of the Energy Transformation issued a report in January 2019 (IRENA, 2018g) that outlines these geopolitical consequences. It points out that the energy transformation will create new energy leaders, strengthening the influence of some countries with large investments in renewable energy technologies.

Fossil fuel exporters may see a decline in their global reach and influence unless they adapt their economies for the new energy age. The report concludes that, overall, the benefits of the energy transformation will outweigh the challenges, but only if the right policies and strategies are in place.

Although policy action needs to be accelerated globally, there are some positive developments. For instance, the European Commission recently proposed a comprehensive climate strategy for achieving a carbon-neutral European economy by 2050 (EC, 2018b). The strategy aligns closely with the Paris climate goals, and its implementation could have positive impacts on gross domestic product (GDP) in an optimistic case, and that health benefits greatly outweigh the costs of climate actions. This strategy is one of the most important steps taken recently to accelerate the pace of the global energy transition. Some other countries in other regions have also targeted zero net emissions by 2050, yet implementation is still lagging overall.

New studies also are exploring how the world could transition to a 100% renewable-based power system, and these studies show that such a transformation is feasible (Bogdanov *et al.*, 2019). It is not just countries that have interest; regions, cities and firms also are exploring ways in which they could transition fully to renewable energy.

Box 1. CLIMATE CHANGE IS ACCELERATING

The trend in long-term global warming continued in 2018, which also happened to be the fourth warmest year on record. The 20 warmest years on record have all occurred in the past 22 years and top 4 were in the past 4 years alone, according to the World Meteorological Organization (WMO, 2018). The IPCC special report on the impacts of global warming of 1.5 °C (IPCC, 2018) reports that for the decade 2006-2015 the average global temperature was 0.86 °C above the pre-industrial baseline. For the most recent decade (2009-2018) the average temperature was about 0.93 °C above the baseline, and for the last five years (2014-2018) it was 1.04 °C above the baseline.

Tropical cyclone numbers were above average in all four Northern Hemisphere basins in 2018, with 70 cyclones reported by 20 November of that year, compared to the long-term average of 53 cyclones per year (WMO, 2018). The Northeast Pacific basin was extraordinarily active, with an Accumulated Cyclone Energy that was the highest since reliable satellite records began.

Europe experienced heat and drought through the late spring and summer of 2018, leading to wildfires in Scandinavia. In July and August of 2018, north of the Arctic Circle, many record high temperatures were registered, as well as record long periods of high temperatures. Both Japan and the Republic of Korea saw new national heat records (41.1 °C and 41.0 °C, respectively) (WMO, 2018).

Eastern Australia experienced significant drought during 2018. Severe drought affected Uruguay and northern and central Argentina in late 2017 and early 2018, leading to heavy agricultural losses. British Columbia in Canada broke its record for the most area burned in a fire season for the second successive year (WMO, 2018). The US state of California suffered devastating wildfires, with November's Camp Fire being the deadliest fire in over a century for the country. One estimate has put the economic cost of the wildfires in California in 2018 at USD 400 billion (AccuWeather, 2018).

Climate extremes are having negative impacts on agriculture, which could reverse gains made in ending malnutrition, and new evidence shows a rise in world hunger after a prolonged decline. In 2017 the number of undernourished people increased to an estimated 821 million, around 10% of the world population, from 784 million in 2015 (WMO, 2018).

These examples show that climate change is not a distant, future problem. Instead the impacts of climate are already large and are being felt today – and are growing at an alarming pace.

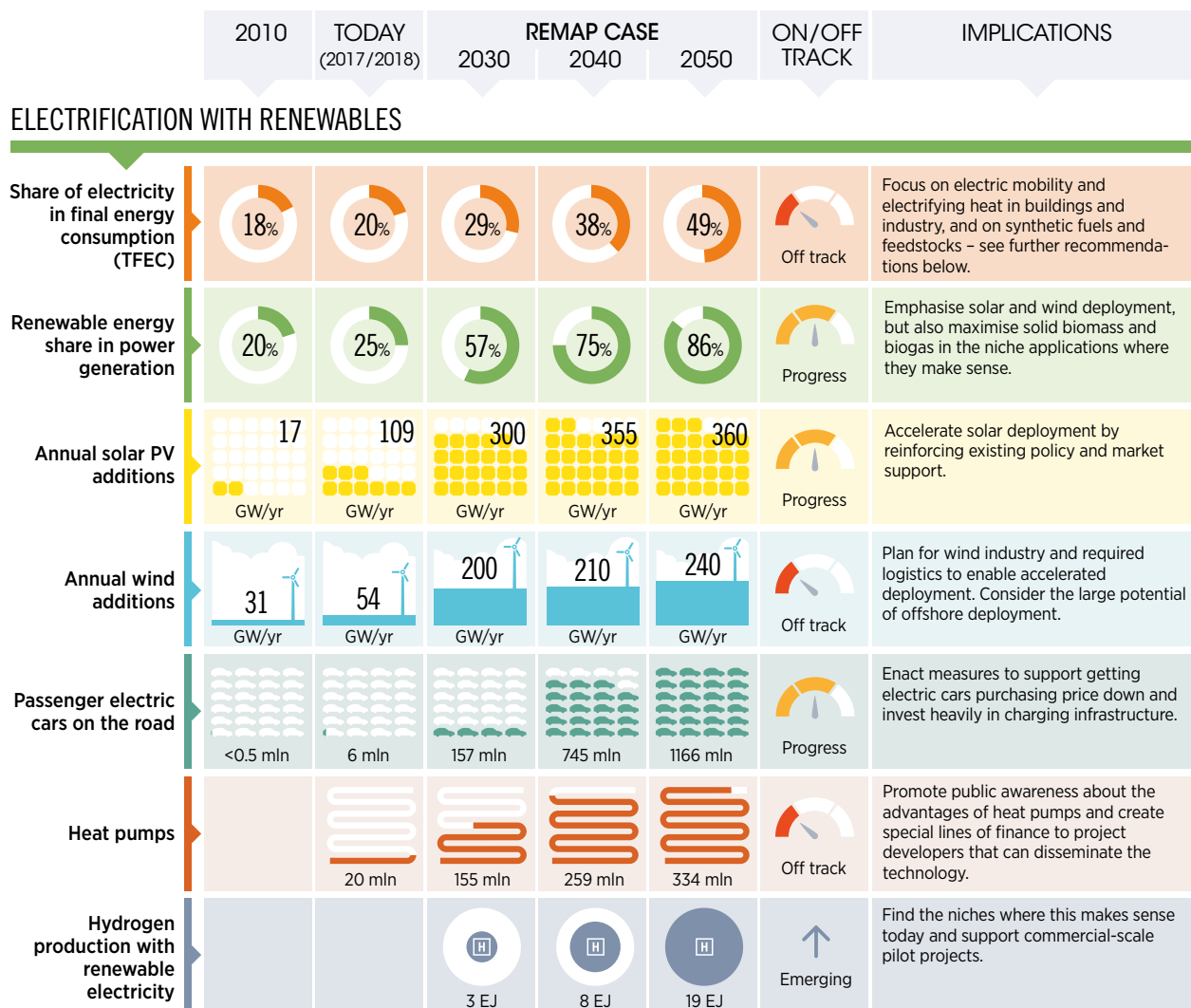
A PATHWAY FOR THE TRANSFORMATION OF THE GLOBAL ENERGY LANDSCAPE

The global energy transformation is more than a simple transformation of the energy sector – it is a transformation of our societies and economies. The energy transformation is multi-faceted, and is evolving in terms of technologies, socio-economics, institutional drivers and forms of finance. This report outlines the need to prepare for an energy system with much higher shares of variable renewable power, for broader innovation, and for strategic planning to increase investments and avoid social stresses and economic problems.

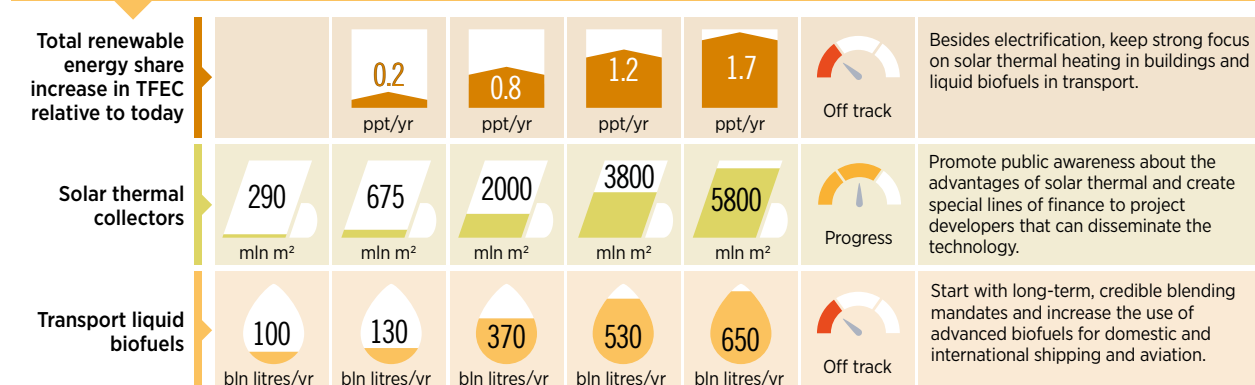
Figure 2 outlines the key indicators that are needed to move the world from where it is today to where it would need to be in 2050, as detailed in the REmap Case. The indicators show that significant acceleration is needed across a range of sectors and technologies, ranging from deeper end-use electrification of transport and heat powered by renewables, to direct renewable use, energy efficiency and infrastructure investment. The following sections go into more detail about the types of measures, technologies and changes that are needed.

Figure 2. A roadmap to 2050: tracking progress of key energy system indicators to achieve the global energy transformation

Progress that is needed for key indicators to achieve the REmap Case



RENEWABLE ENERGY IN END-USES



Notes: 1) TFEC – total final energy consumption; 2) Utility and distributed solar PV total additions (new as well as repowering); 3) Onshore and offshore wind total additions (new as well as repowering); 4) Passenger cars exclude 2/3 wheelers, buses and other electric mobility transport modes; 5) Heat pump estimates based on available data; 6) Includes conventional and advanced biofuels – ethanol, biodiesel and biojet; 7) Modern renewables excludes traditional uses of biomass, which are observed in non-OECD countries in the buildings sector for cooking, space heating, etc.; 8) Energy efficiency intensity is measured in terms of primary energy use divided by GDP, this shows the amount of energy required to generate one unit of GDP – improvements of that measure are shown here; 9) Stationary battery storage includes batteries deployed along with decentralised PV systems as well as utility-scale batteries; 10) Fossil fuel demand includes non-energy uses. The on/off track shown in the infographic indicates the tracking progress to achieve 2050 targets with respect to current levels (2017/18). LCOE refers to levelized cost of electricity.

	2010	TODAY (2017/2018)	REMAP CASE			ON/OFF TRACK	IMPLICATIONS
			2030	2040	2050		
ENERGY EFFICIENCY							
Energy intensity improvement rate	2000-2010 1.2% per year	2010-2017 2.3% per year	2016-2030 3.3% per year	2016-2040 3.3% per year	2016-2050 3.2% per year	Off track	Promote efficiency standards and efficient appliances and create conditions for project developers that speed deployment of energy efficiency technologies.
Total final energy consumption per capita	51 GJ per cap	53 GJ per cap	43 GJ per cap	41 GJ per cap	38 GJ per cap	Off track	

ELECTRICITY GENERATION AND CONSUMPTION ASPECTS

Onshore wind LCOE	80 USD/MWh	56 USD/MWh	50 USD/MWh	45 USD/MWh	40 USD/MWh	On track	Promote competitive bidding for solar and wind capacity additions and reform market regulation to accommodate these sources
Solar PV LCOE	347 USD/MWh	81 USD/MWh	58 USD/MWh	48 USD/MWh	38 USD/MWh	Progress	
Smart meters in the residential sector		25% of households	50% of households	77% of households	82% of households	Progress	Accelerate smart meter installations in existing buildings and mandate their installation in new buildings.

TOTAL FOSSIL FUEL DEMAND

Oil demand	87 mln barrels/day	95 mln barrels/day	60 mln barrels/day	41 mln barrels/day	22 mln barrels/day	Off track	Increase liquid biofuels and electrification in the transport sector. Support pilot projects for bio-refineries and synthetic feedstock use for petrochemicals in industry.
Natural gas demand	3307 bcm/yr	3752 bcm/yr	4000 bcm/yr	3400 bcm/yr	2250 bcm/yr	Off track	
Coal demand	4963 Mtce/yr	5357 Mtce/yr	3190 Mtce/yr	2000 Mtce/yr	713 Mtce/yr	Off track	Stop building new coal power plants and accelerate the retirement of existent coal power facilities. Need for new carbon-free iron making processes.
Total fossil fuel reduction relative to today			-20%	-41%	-64%	Off track	End subsidies for fossil fuels. Support training programmes to retrain displaced workers from fossil fuel industries.

ENERGY-RELATED CO₂ EMISSIONS

Total CO₂ reduction relative to today			-27%	-48%	-71%	Off track	Correct market distortion and price the external costs of CO ₂ . Avoid fossil fuel infrastructure stranding by avoiding unnecessary investment in new production and distribution.
Emissions per capita	4.3t CO ₂ per cap	4.6t CO ₂ per cap	2.9t CO ₂ per cap	2.0t CO ₂ per cap	1.1t CO ₂ per cap	Off track	

Sources: IRENA estimates; GWEC (2019) for today's wind power additions; BNEF (2019) for today's PV power additions; IEA (2011, 2018d) for coal, gas and oil demand in 2010 and 2017; ZSW (2019) for electric cars on the road; AEE INTEC (2018, 2012) for solar thermal collectors in 2010 and 2017.

ENERGY-RELATED EMISSIONS

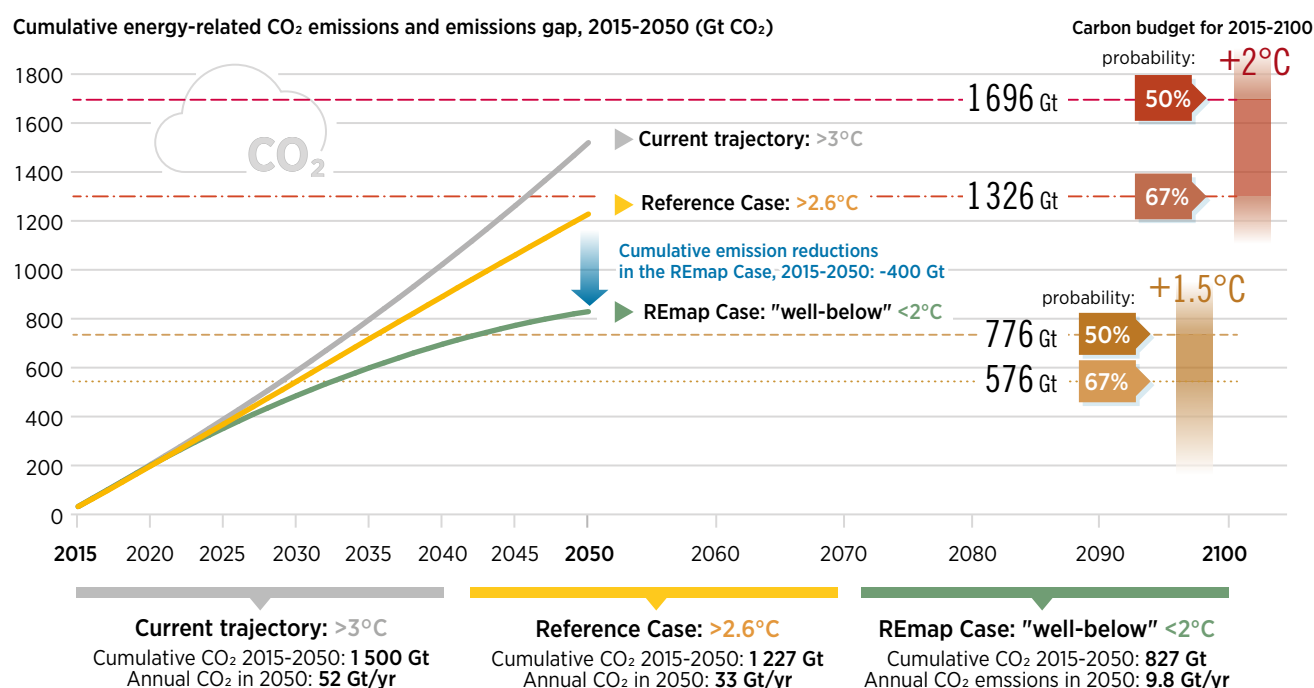
Based on a carbon budget from the latest IPCC special report on the impacts of global warming of 1.5°C (IPCC, 2018), the Reference Case in this report shows that the global energy-related CO₂ budget will run out at the latest by 2030 (based on the IPCC assessment of a 50% confidence level for 1.5°C). To set the world on a pathway towards meeting the aims of the Paris Agreement, energy-related CO₂ emissions would need to be scaled back by at least an additional 400 gigatonnes (Gt) by 2050 compared to the Reference Case; in other

words, annual emissions would need to be reduced by around 3.5% per year from now until 2050 and continue afterwards.

Energy-related emissions would need to peak in 2020 and decline thereafter. By 2050 energy-related emissions would need to decline by 70% compared to today's levels. While this report is focused only on energy-related CO₂ emissions, additional efforts are needed to reduce emissions in non-energy use (such as using bioenergy and hydrogen feedstocks); industrial process emissions; and efforts outside of the energy sector to reduce CO₂ emissions in agriculture and forestry.

Figure 3. REmap offers a pathway for a well-below 2°C climate target, towards 1.5°C

Cumulative energy-related CO₂ emissions for the period 2015-2050 and emissions budgets for 2015-2100 for 1.5°C and 2°C scenarios (Gt CO₂)



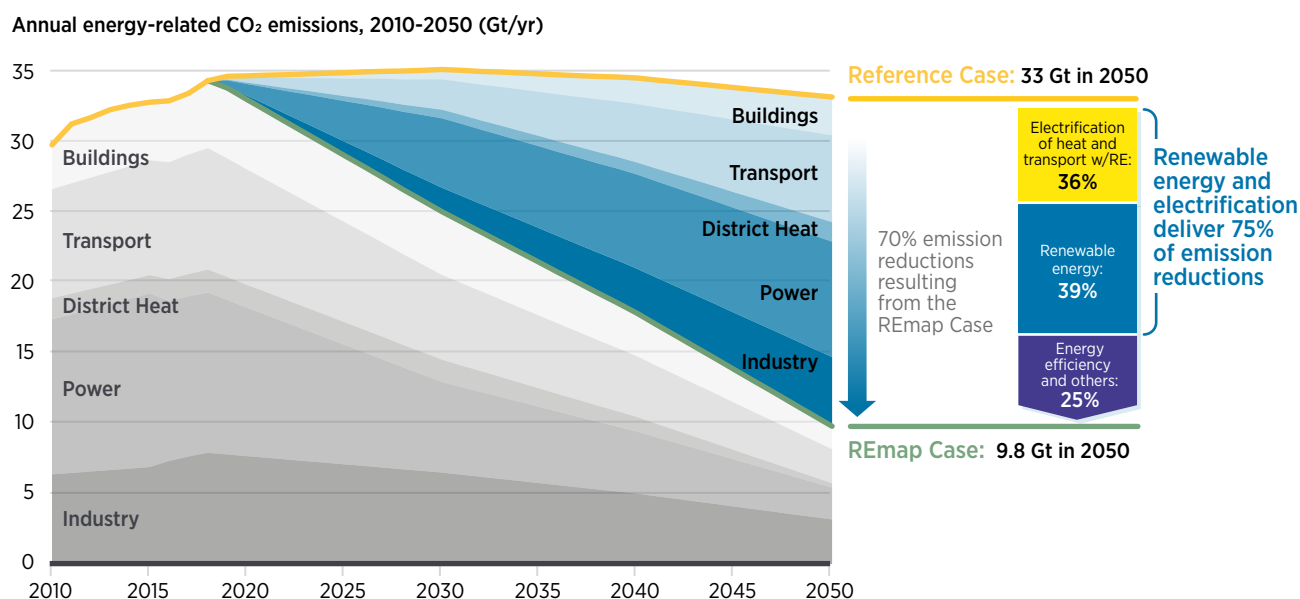
The global carbon budget is set to run out by 2030 based on current and planned policies. Energy-related emissions would need to fall by 3.5% per year to the world to meet the aims of the Paris Agreement.

The REmap Case presented in this report outlines an aggressive, yet technically and economically feasible, route for accelerated action. It shows that the accelerated deployment of renewables, combined with deep electrification and increased energy efficiency, can achieve over 90% of the energy-related CO₂ emissions reductions needed by 2050 to reach the well-below 2 °C aim of the Paris Agreement.³ Electrification with renewable power is key, together making up 60% of the mitigation potential; if the additional reductions from direct use of renewables are considered, the share increases to 75%. When adding energy efficiency, that share increases to over 90%.

Not acting to mitigate the effects of climate change will be much costlier. Existing plans and policies (the Reference Case in this study) will result in additional costs of USD 96 trillion related to air pollution and negative climate impacts by 2050 compared to the accelerated scale-up of renewables, energy efficiency and other technologies identified in the REmap Case. Avoiding these costs under the REmap transition pathway would require additional expenditures. Nevertheless, the cumulative benefit of the REmap Case by 2050 would be in the range of USD 65 trillion to USD 160 trillion.

Figure 4. Renewables and energy efficiency, boosted by substantial electrification, can provide over 90% of the necessary reductions in energy-related carbon emissions

Annual energy-related CO₂ emissions in the Reference Case and reductions in the REmap Case, with the contribution by sector, 2010-2050 (Gt/yr)



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

Annual energy-related CO₂ emissions under current and planned policies – the Reference Case – are expected to remain flat, at 33 Gt CO₂ per year in 2050, but must be reduced by 70% to bring temperature rise to the well-below 2°C climate goal – as in the REmap Case. Electrification, renewable energy and energy efficiency measures provide over 90% of the reductions required by 2050. Renewable power and electrification of heat and transport alone reduce emissions by 75%.

³ According to the IPCC, 67% 2°C up to 1.326 Gt; the REmap Case, with 827 Gt by 2050 is well below the 2°C pathway, and towards the 50% 1.5°C. More information about the carbon budget, and assumptions for non-energy greenhouse gas emissions, is available online at www.irena.org.

There are other risks of not taking action now. Infrastructure investment decisions today lock in energy use and emissions for decades. Investment in long-term assets, such as in fossil fuel infrastructure and inefficient building stock, continue unabated. This not only risks locking in emissions, but will add significant liability to the balance sheets of energy companies, utilities, investors and property owners. The energy transition will result in some asset stranding, totalling USD 11.8 trillion overall by 2050 in the REmap Case, of which the highest share occurs in buildings (63%) and upstream investments in fossil fuels (28%). However, delaying action will almost double the amount of stranded assets, adding an additional USD 7.7 trillion and increasing the total value of stranded assets to USD 19.5 trillion by 2050 (equivalent to total US GDP in 2018). Delaying action therefore risks missing climate targets and may require relying on costly and unproven negative emission technologies.

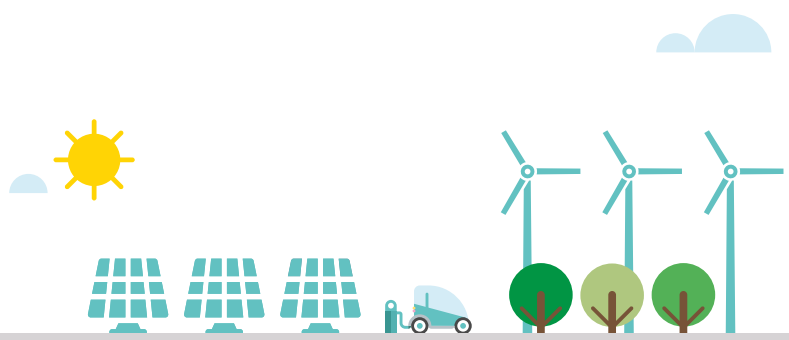
A TRANSFORMED ENERGY SYSTEM

New and credible scenarios all point in the same direction: that renewables and energy efficiency, in combination with electrification, are the key ingredients of a successful energy transition (Gambhir, n.d.; IPCC, 2018). The importance of renewables and energy efficiency for accelerating the energy transition is a generally agreed insight among various energy scenarios. However, long-term energy scenarios need to be further improved for long-term energy strategy development and policy-making purposes.⁴

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

IRENA's REmap Case shows that the share of modern renewable energy would need to rise from 10% of total final energy consumption (17% including traditional uses of bioenergy) today to two-thirds in 2050. This is well above the Reference Case, which will yield only about a one-quarter share for renewables in total final energy. If viewed in annual terms, growth in the renewable share will increase only around 0.25 percentage points per year, to 25% by 2050; whereas the REmap Case accelerates this growth six-fold to 1.5 percentage points (ppt) per year.

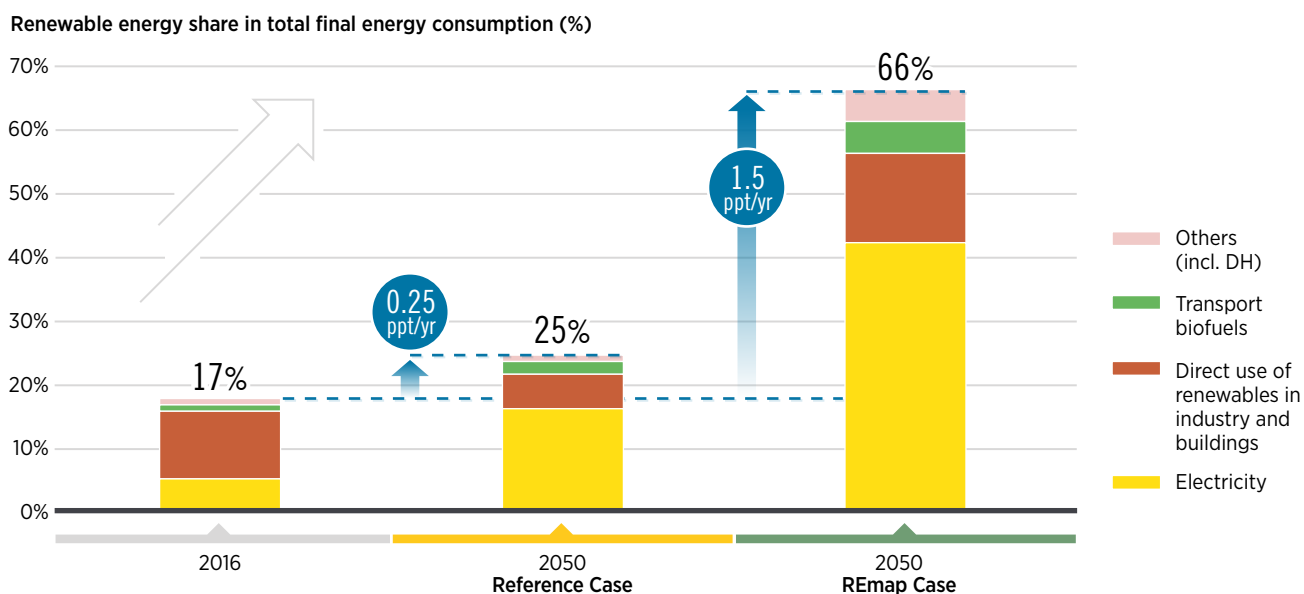
The share of renewables in power generation would rise from 25% today to 86% in 2050. About 60% of total generation in 2050 would be accounted for by variable renewables, such as solar and wind. Total annual renewable power generation would rise from 7 000 TWh at present to 47 000 TWh by 2050 – a seven-fold increase.



⁴ More insights from the long-term energy scenarios campaign are available at <https://www.irena.org/energytransition/Energy-Transition-Scenarios-Network/Long-term-Energy-Scenarios-Campaign>.

Figure 5. Renewables share in total final end-use consumption needs to accelerate six-fold compared to current levels

Renewable energy share in total final energy consumption (TFEC, %), Reference and REmap cases, 2016-2050



To enable a match between electricity supply and demand, USD 13 trillion would be invested in enabling grid infrastructure and power system flexibility, an increase of around USD 4 trillion compared to the Reference Case. Furthermore, legislative and regulatory changes are needed. Grid codes and electricity pricing mechanisms would need to be changed to allow more widely for energy consumers to produce, and consume, their own energy (turning them into “prosumers”) and to promote digitalisation technologies that can help manage loads (IRENA, 2019b).

The energy intensity improvement rate⁵ would need to increase to 3.2% per year. This is higher than the improvements in recent years (2.3%) or projected in the Reference Case (2.4%). The gap between the rate in the Reference Case and what is needed in REmap can be filled through several key

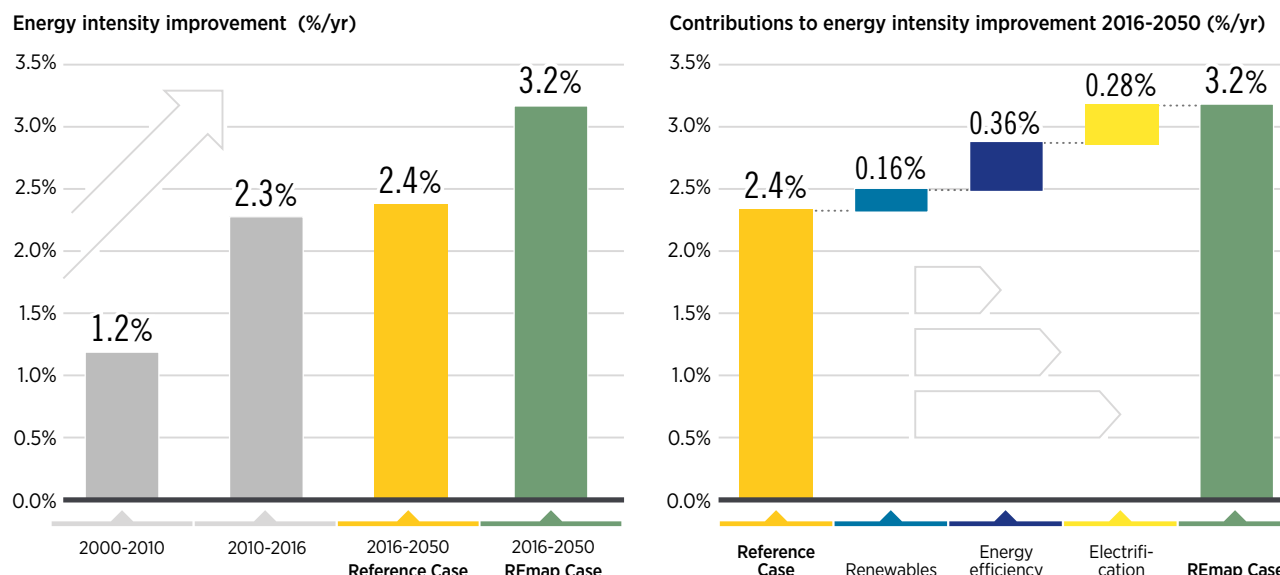
The share of renewables in the world's total final energy consumption has to increase six times faster to meet agreed climate goals.

means. One is the deployment of energy efficiency measures, which contribute to nearly half of the reductions needed in the REmap Case compared to the Reference Case (0.36 percentage points per year). The others are increased electrification of heat and transport applications (0.29 ppt per year) and uptake of renewables in the power and end-use sectors (0.16 percentage points per year).

⁵ Energy efficiency for this indicator is defined as the ratio between the primary consumption of energy and GDP. The indicator is expressed as a change in the ratio in compound annual growth rate of energy intensity of GDP measured in purchasing power parity (PPP) terms.

Figure 6. Energy intensity improvements broken down into higher electrification of end-use applications, renewable energy deployments and energy efficiency

Energy intensity improvement rate (%/yr), Reference and REmap Cases, 2016-2050



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

Energy intensity can be improved by:

- **Scaling up solar, wind and other renewables,**
- **improving energy efficiency,**
- **electrifying transport and heat,**
- **structural change in transport and industry.**

A circular economy will play an increasingly important role in forthcoming decades, contributing to reductions in energy consumption and increases in the efficiency of resource use, as well as improvements in material efficiency in industry due to innovations. Advanced digital and communication technologies with enhanced connectivity make it possible to better optimise the transport of heavy goods, which will eventually reduce the overall energy consumed by freight. In buildings, retrofits to improve efficiency would need to accelerate significantly, and all new buildings in cold and moderate climate zones would need to be built to zero energy standards beginning in the next decade.

Also over the period, traditional uses of bioenergy, largely for cooking, would be phased out, replaced with energy technologies such as modern cookstoves, electric cooking and liquefied petroleum

gas (LPG). It is also estimated that just under 1 billion people do not have access to a reliable electricity supply; renewable power technologies, including mini- and off-grid solutions, are proving key in enabling higher access rates.

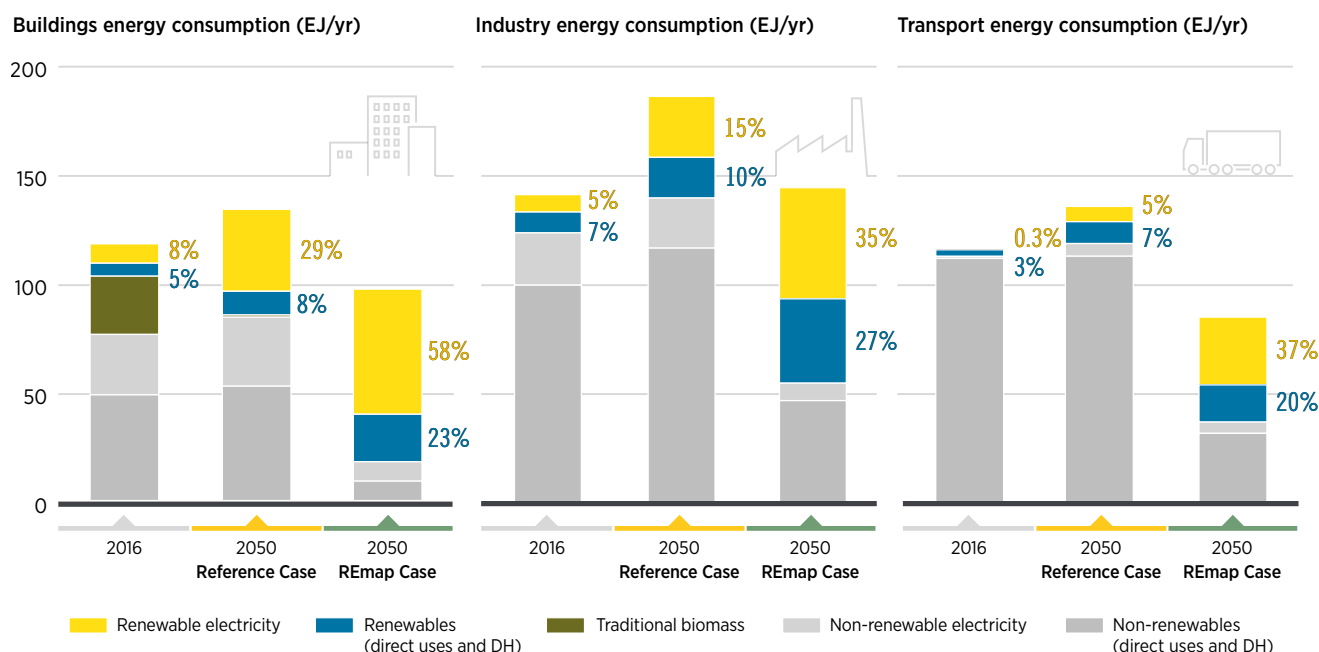
Electrifying end-use sectors using renewable power leverages synergies with energy efficiency measures and brings additional energy intensity improvements. One reason is that solar and wind plants produce electricity that has minimal energy conversion losses (and energy intensity is based on primary energy), in contrast to the much lower efficiencies of using fossil fuels for generation and end-uses. Also, electric drives and heat pumps are much more efficient than comparable fossil fuel-based

systems. Increased electrification reduces growth in overall primary energy use if supplied with renewable power, and allows a given amount of renewable energy to yield a higher percentage share in the energy system at the same time. This important synergy between renewable energy and energy efficiency is often overlooked and can address dual mandates of increasing efficiency while increasing renewable shares (IRENA, 2017d).

In the REmap Case, global energy demand in 2050 would be slightly lower than today's level, despite significant population growth (an additional 1.7 billion by 2050) and a larger global economy (triple by 2050), because of higher energy efficiency.

Figure 7. Scaling up renewables not just for power, but also for heat and transport

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



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

Electricity consumption in transport would rise to 43% and in buildings 68% of sector energy by 2050. Of that electricity, 86% would come from renewable sources.

The share of electricity in final energy use would increase from 19% to nearly 50%. Electromobility and electric heating would play increasing roles. By 2050 around 70% of all cars, buses, two- and three-wheelers and trucks would be powered by electricity. Also, around 8% of the electrification share in final consumption would be attributed to renewable hydrogen (for instance, used as a feedstock in industry) and other transport fuels. In total 19 exajoules (EJ) of renewable hydrogen would be consumed by 2050, a large number but one that has also been substantiated in other studies (Teske, 2019). Sustainably sourced bioenergy is also an important component of the energy transition. Advanced liquid biofuels, especially for use in aviation, heavy freight and shipping, will be crucial in some sectors and will need to be scaled up (IRENA, 2016a). Bioenergy is also important in applications for which renewable power technologies are less suitable, such as certain types of high-temperature process heat in industry. It is a key enabler in the chemicals and petrochemical sectors, where processes often require both heat and feedstocks to manufacture products such as high-value chemicals. Primary bioenergy demand would double compared to today's level, to around 125 EJ by 2050 in the REmap Case. The market size for liquid biofuels in 2050 would need to grow four-fold, from 130 billion litres today to 652 billion litres annually by 2050.

AN ELECTRIFIED FUTURE

As this report makes clear, harnessing the synergy between low-cost renewable power and end-use electrification is the key solution to driving down energy-related CO₂ emissions. While the REmap Case sets forth a trajectory to achieve more than 70% emissions reductions compared to the Reference Case trajectory, 60% of these emissions reductions are achieved through renewable power and by electrifying heat and transport applications.

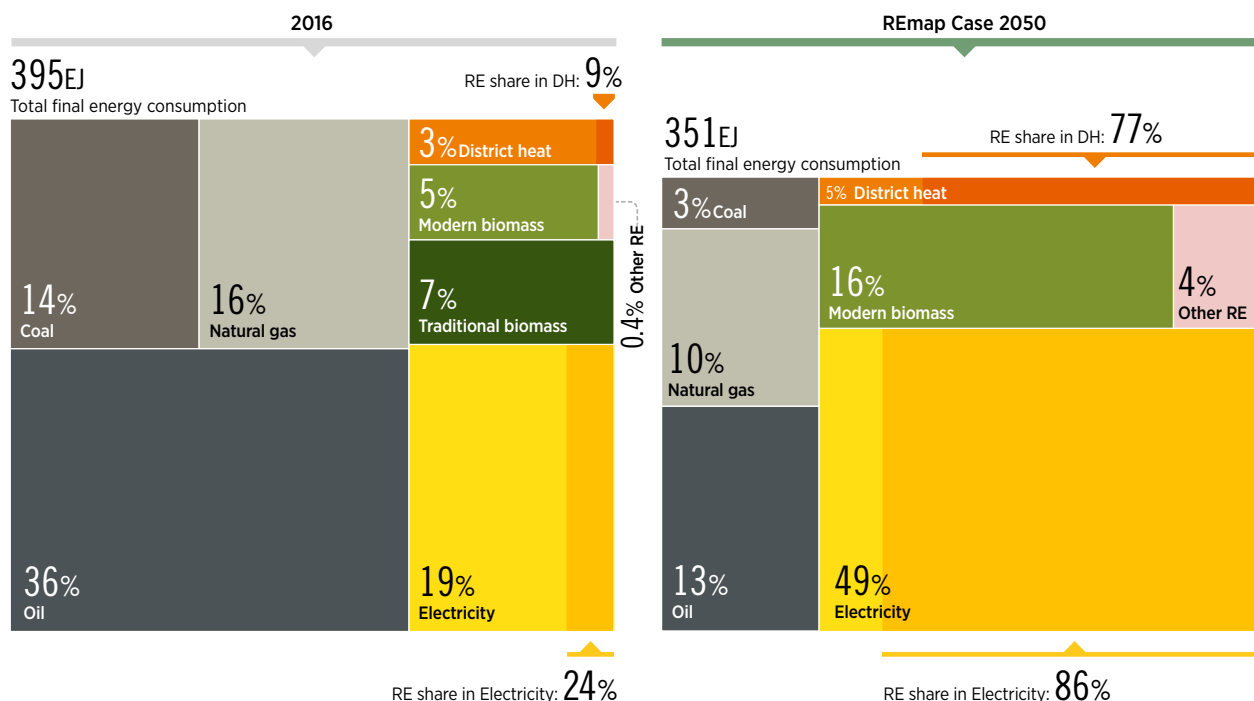
The increasingly electric energy system would transform how the power sector and demand interact. By 2050, 86% of electricity generation would be renewable, and 60% would come from solar and wind. Wind and solar PV would dominate expansion, with installed capacities of over 6 000 GW and 8 500 GW, respectively, in 2050.

Matching supply and demand when so much variable renewable energy (VRE) is being produced will require an increasingly smart, digitalised and flexible power system (IRENA, 2019c). The power system will be different than it is today, with a much higher share of distributed energy sources, electricity trading and demand response.

The share of electricity in final energy 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 need to increase from just 1% today to over 40% by 2050.

The transport sector sees the largest transformation. The number of EVs would reach over 1 billion in 2050. Urbanisation is occurring rapidly worldwide, and clean transport and disruptive service solutions are necessary to keep cities liveable. Trams, buses, two- and three-wheelers, and passenger vehicles powered by renewable-based electricity would need to become the predominant forms of city transport, as well as non-motorized vehicles. This can be achieved through smart city planning and the roll-out of charging and supply infrastructure, as well as smart regulation (IRENA, 2019b). Increased connectivity and



Figure 8. Electricity becomes the main energy source by 2050*Breakdown of total final energy use (TFEC) by energy carrier in 2016 and REmap Case 2050 (EJ)***Total final energy consumption breakdown by energy carrier (%)**

Note: For electricity use, 24% in 2016 and 86% in 2050 comes from renewable sources; for district heating, this share is 9% and 77%, respectively. DH refers to district heat.

big data, together with autonomous driving and sharing behaviour, can bring additional mobility services solutions, which will help in driving down energy use and increasing energy efficiency in transport.

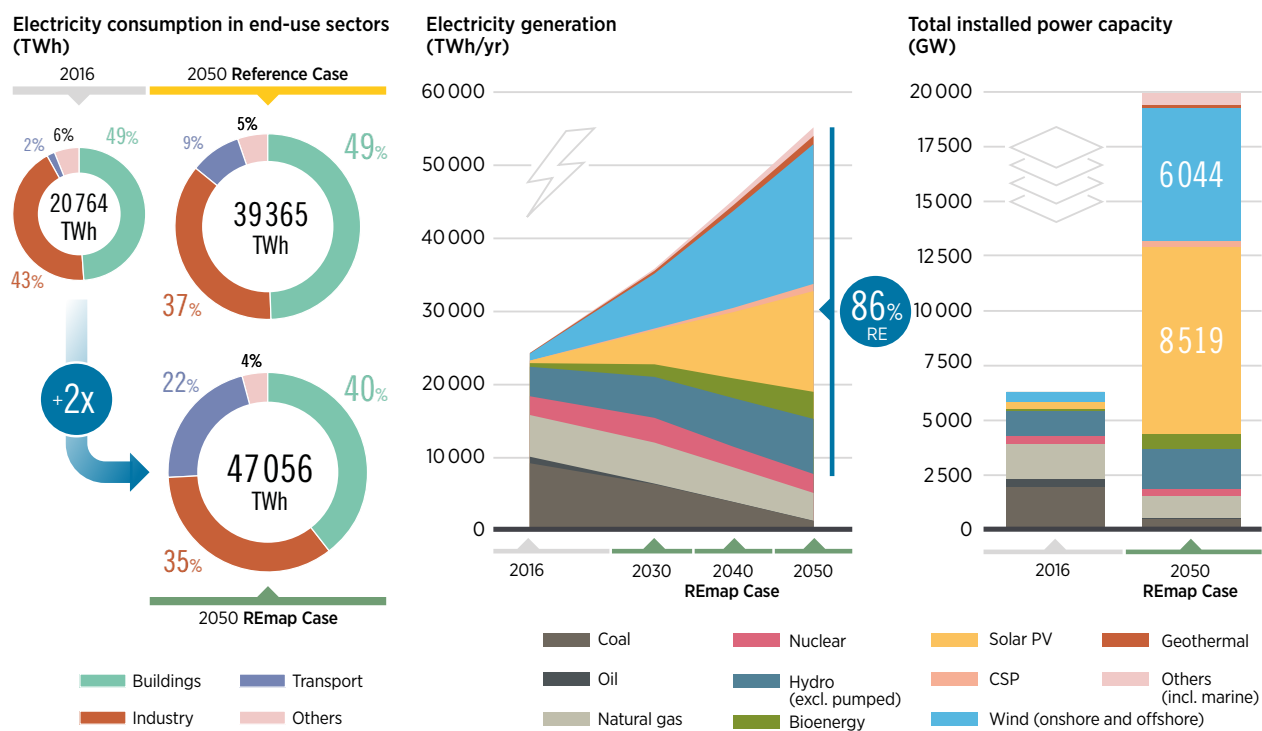
Developing and deploying renewable heating and cooling solutions for buildings, urban development projects and industries is also key. For example, the district heating network of Aarhus, Denmark uses both an electric boiler and an electric heat pump, part of the country's plan to satisfy half its electricity demand using wind power (IRENA, 2017e). Moreover, electric heating and cooling offers important flexibility in demand, allowing greater coupling between the power sector and end-use sectors, and greater utilisation of variable generation sources. For instance, the International

Scaling up electricity from renewables will be crucial for the decarbonisation of the world's energy system.

Energy Agency (IEA), notes that the use of energy for space cooling is growing faster than for any other type of energy use in buildings, having more than tripled between 1990 and 2016, and that rising demand for space cooling is already putting enormous strain on electricity systems in many countries, while similarly driving up emissions (IEA, 2018d). Therefore, addressing cooling demand is crucial to address emissions in the buildings sector.

Figure 9. Wind and solar power dominate growth in renewable-based generation

Electricity consumption by sector (TWh, %), electricity generation mix (TWh/yr) and power generation installed capacity (GW) by fuel, REmap Case, 2016-2050



Note: In electricity consumption, 24% in 2016 and 86% in 2050 is sourced from renewable sources. CSP refers to concentrated solar power

By 2050, solar power, with 8 500 GW installed capacity, and wind, with 6 000 GW, would account for three-fifths of global electricity generation. Electricity consumption in end-use sectors will more than double from today's level.

Cities and municipalities need to encourage the uptake of renewables in their built environment, too, and also adopt efficient, centralised district systems which can utilise renewable power and store heat for use later when necessary. In the buildings and industry sectors the number of heat pumps would increase to over 334 million, meaning that more than 16 times the number of these highly efficient heating technologies would be installed than are in operation today. Electrification, automation and connectivity would help reduce energy losses, foster behaviour change towards less energy consumption and help distributed renewable energy to increase its penetration over time.

Particularly in the buildings sector, energy efficiency is the priority for new buildings as well as for retrofitting existing stock. The combination of energy efficiency and renewables yields economic solutions.

The power sector would more than double in size by 2050 and would be fundamentally transformed due to the addition of over 14 000 GW of new solar and wind capacity. The sector will need greater flexibility to accommodate the daily and seasonal variability of solar and wind power. Flexible measures will be required across a wide spectrum of technologies and market solutions (IRENA, 2018c). For instance, interconnections between national or regional grids can help to balance supply and demand for power.

Smart meters, which can enable real-time pricing – thereby helping to shift demand to times when electricity supply is plentiful – would need to be installed in 80% of residential units, and 9 TWh of storage

(excluding pumped hydropower) would be available to the grid, along with 14 TWh from EV batteries.⁶ Electrolyser capacity also would need to grow substantially to produce renewable hydrogen. Demand-side management (for instance in industry) which can shift load to times of peak electricity supply, other forms of electricity storage (for instance in buildings to supply electricity during evening hours) and smart grids would facilitate further the integration of variable renewables, while real-time market pricing would enable the value of power generation to be assessed at different times. New regulatory frameworks must allow new entrants into the power market and reflect the evolving roles of utilities and consumers and prosumers.

Some of the needed flexibility would be on the supply side, made possible by storage, grid interconnections, and new market and operation rules. The demand side, however, has a significant role to play as well. For example, EV charging, heat pump use or hydrogen production can be adjusted to match the variable generation from renewable sources or to provide storage. EVs offer storage for a few hours, while heat can provide storage for days and hydrogen can store energy for entire seasons.

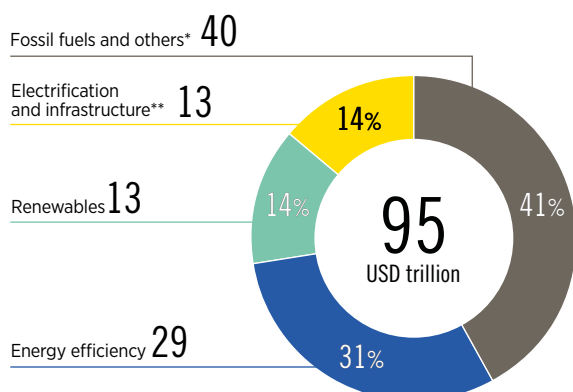
INVESTMENTS, COSTS AND SUBSIDIES

Meeting growing global energy demand over the coming decades will require significant increases in investment, regardless of the path the world takes. Cumulative investments in the energy system to 2050, including infrastructure and efficiency, will total almost USD 95 trillion in the Reference Case, and would increase to USD 110 trillion in the REmap Case. A pathway towards meeting the aims of the Paris Agreement will require a shift in investments away from fossil fuels towards renewable energy, electrification technologies and efficiency that would require an additional USD 15 trillion over the period to 2050.

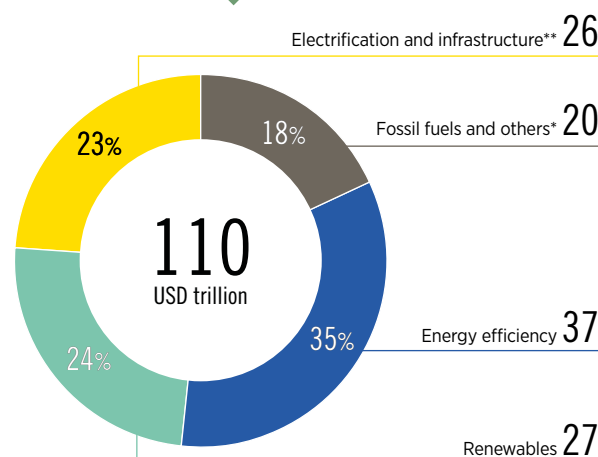
Renewable power technologies are increasingly the least-cost electricity supply options available. The renewable energy market would grow quickly as costs continue to decline, as technologies improve and as innovation brings additional applications. A huge market would emerge with almost USD 90 trillion of investments needed for renewable energy, electrification technologies and energy efficiency by 2050 in the REmap Case. In 2030 the renewable energy market would reach USD 730 billion annually, and in 2050 it would reach USD 680 billion annually. This compares to USD 332 billion invested in

Figure 10. Shifting investment to energy efficiency, renewables and the electrification of heat and transport
Cumulative investments for Reference and REmap cases, 2016-2050 (USD trillion)

Reference Case cumulative investments, 2016-2050
(USD trillion)



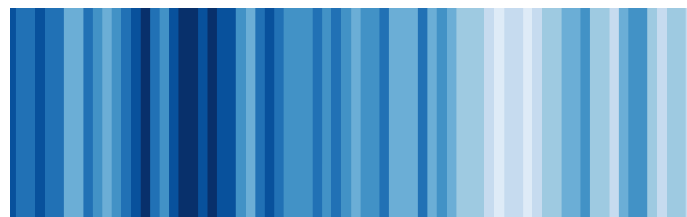
REmap Case cumulative investments, 2016-2050
(USD trillion)



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

6 Considering 50% availability of EVs to the grid and 25% for electric two- and three-wheelers by 2050.

The REmap Case increases investments in the global energy system by USD 15 trillion, and shifts investment into electrification, renewable energy and energy efficiency technologies, which together, would make up four-fifths of the cumulative energy sector investments over the period to 2050.



2018 (including large hydropower). Annual investments therefore need to more than double by the end of the next decade.

However, an energy system based heavily on renewables would be different than past systems and would require significant investments in power grids, complementary infrastructure and energy flexibility. In the Reference Case, investments for these would amount to USD 9 trillion. In the REmap Case, an additional USD 4 trillion would be required, for a total of USD 13 trillion.

When accounting for these additional investment needs, operation and maintenance, and fuel savings, the incremental energy system costs in the REmap Case (compared to the Reference Case) would reach USD 1 trillion in the year 2050. Cumulative additional system costs over the period to 2050 add up to USD 21 trillion. These additional costs, however, are small compared to the benefits. The huge reduction in the use of fossil fuels would cut air pollution, improve health (and reduce healthcare costs) and reduce damage from the impacts of climate change. The resulting savings would add up to an average of USD 5.3 trillion annually by 2050, more than five times larger than the additional system costs of decarbonisation that year.

Furthermore, the energy sector has for virtually all of the modern era of energy use operated under, and often actively sought, a range of fossil fuel subsidies that have distorted market functioning. In 2015 total subsidies to the energy sector were at least USD 605 billion, with fossil fuel subsidies

accounting for around three-quarters (USD 450 billion) of this, while renewable power generation subsidies were around USD 110 billion and subsidies to liquid biofuels were USD 25 billion.⁷ Therefore, in recent years, fossil fuel subsidies have outweighed renewable subsidies by a factor of around four. Under current and planned policies of the Reference Case, and assuming similar subsidy policies, overall energy sector subsidies would increase to around USD 865 billion annually by 2050.

In the REmap Case, annual energy sector subsidies will fall from at least USD 605 billion per year in 2015 to around USD 470 billion per year in 2050, a reduction of around USD 135 billion compared to 2050 (this is USD 396 billion per year lower than in the Reference Case). In the REmap Case, inefficient fossil fuel subsidies are largely eliminated by 2050, but subsidies remain for carbon capture and storage in industry given the difficulty of reducing process emissions. The REmap Case would see a rapid rebalancing of subsidy efforts towards energy efficiency and renewable energy (mostly for retrofitting buildings and using renewables in buildings and industry), although the subsidies would be used to support different types of technologies.

Within renewables, a rebalancing is also required through time as subsidies for power generation technologies decline and are eliminated by 2050, while the subsidies to support the deployment of renewable and energy efficiency technologies needed to decarbonise the industry and transport

⁷ These estimates exclude the implicit subsidies to fossil fuels from unpriced externalities such as the health costs of fossil fuel air pollution and costs stemming from climate change.

sectors would grow. This rebalancing of subsidies from fossil fuels (which will also result in lower consumption, thereby helping to reduce their negative externalities) to renewables will improve the economic efficiency of the energy sector relative to the Reference Case by rebalancing investment away from fossil fuels with their large externality costs.

From now until 2050, the REmap Case would result in a cumulative reduction in fossil fuel subsidies of USD 15 trillion that will occur in the Reference Case (assuming similar subsidy policies). When the increased support for renewables in the REmap Case is included, the net reduction in energy sector subsidies for the period to 2050 would be USD 10 trillion.

Therefore, the savings from reduced externalities and avoided subsidies outweigh the additional energy system costs by a factor of three to seven, resulting in cumulative savings of USD 65 trillion to USD 160 trillion. Or, viewed differently, for every USD 1 spent for the energy transition, there would be a payoff of between USD 3 and USD 7. Moreover, these savings do not take into account the additional benefits of renewable energy deployment and energy efficiency, which include lower water consumption, increased job creation and higher GDP, as well as the positive synergies with Sustainable Development Goals. The analysis also suggests that there would be a general improvement in welfare. These topics are discussed in more detail in the next section.

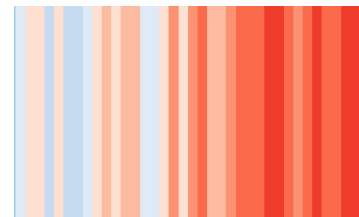
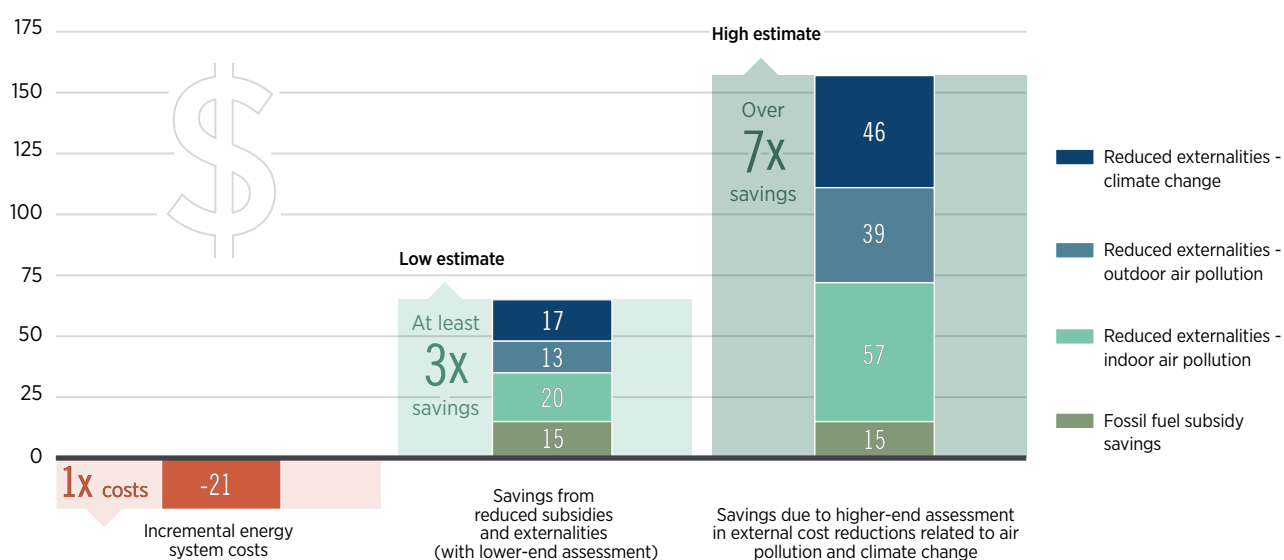


Figure 11. Benefits of the energy transformation compared to expenditures

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

Costs and savings for the period 2016-2050 for the REmap Case, compared to the Reference Case (USD trillion)



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

For every dollar invested in transforming the global energy system, there is a payoff of at least USD 3 and potentially more than USD 7, depending on how externalities are valued.

COMPARISON WITH OTHER ENERGY SCENARIOS

IRENA's REmap analysis can be compared with scenarios from other major energy studies. The assessment of these scenarios shows that there is an emerging consensus on the increasingly important role that renewable power will play in the energy mix in the coming decades.

Many scenarios support the findings of the REmap Case presented in this report, which indicate that decarbonisation of the energy system should rely heavily on renewable energy and energy efficiency. There is consensus on the role of renewable power generation, which for most of the scenarios is above 70% in 2050, as well as on the role of electrification in final energy consumption. The comparison analysis also shows a

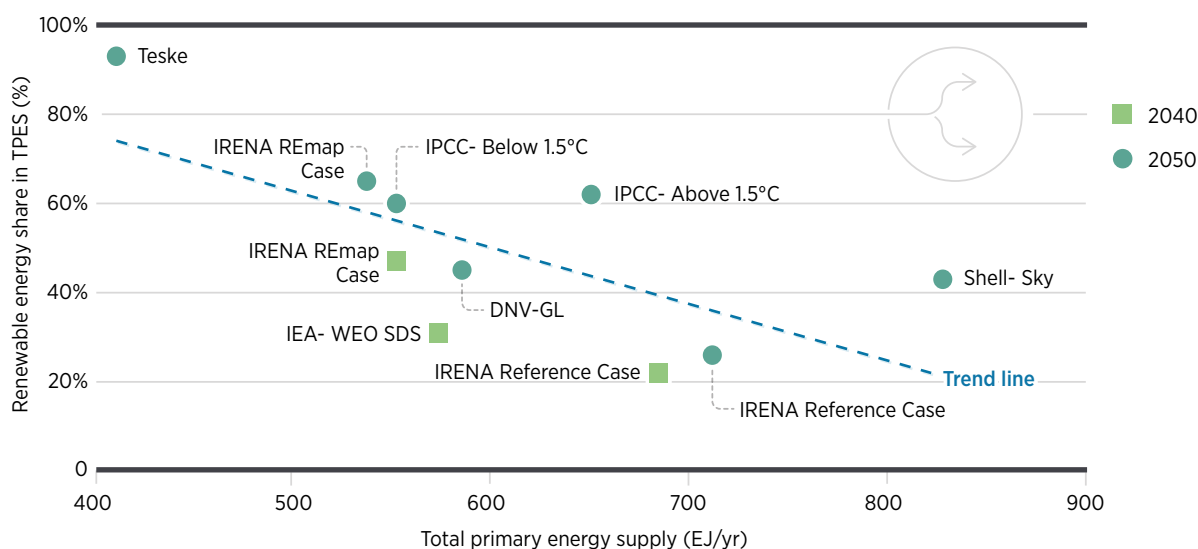
clear correlation between energy demand, energy efficiency and share of renewable energy (Figure 12), and the scenarios with high renewable energy shares are also the ones with higher efficiency and as a result lower overall energy demand.

However, differences can be found in aspects such as the level of electrification in end-use sectors and the level of reduction of CO₂ emissions. The divergence in results can be explained mainly by the different objectives behind the scenarios. For the majority, the analysis is defined by the need to reduce energy-related CO₂ emissions to maintain temperature rise to either 2°C or 1.5°C; others have modelled the energy system in a more business-as-usual perspective.

Figure 12. Renewable energy share and energy demand projections for key scenarios

Renewable energy share (in %) and total primary energy supply (EJ), 2040-2050

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



Higher shares of renewables correlate with reduced energy demand.

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

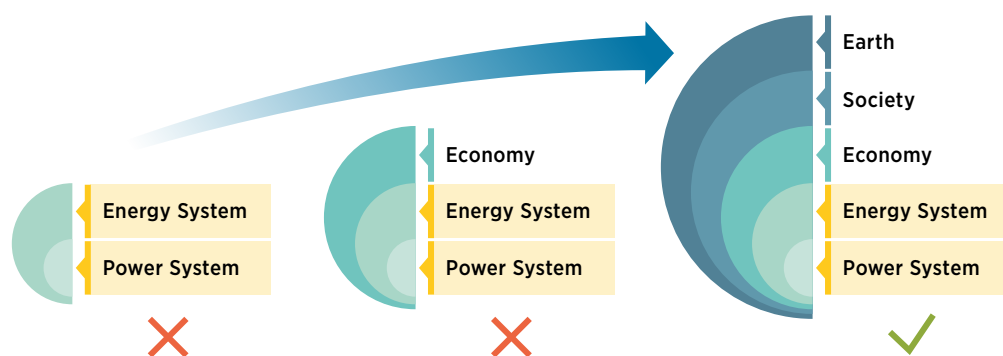
MEASURING THE SOCIO-ECONOMIC FOOTPRINT OF THE ENERGY TRANSITION

The need to bring economic and environmental objectives into closer alignment, and in particular to reduce the climate impacts of a fossil fuel-based world economy, is prompting a profound restructuring of the energy system. For the transition to succeed, policies must be based on a more integrated assessment of the interactions between the evolving energy sector and the wider economy. In an age of urgent climate and sustainability action, these interlinkages extend to the many ways in which human economic activity relates to the planet's natural systems. Figure 13 illustrates the different dimensions of a more holistic approach.

Therefore, the energy transition cannot be considered in isolation from the broader socio-economic system. In fact, the changes in the energy system have impacts throughout the economy.

IRENA's socio-economic footprint analysis provides a comprehensive view of the transition process. It uses integrated models and indicators to measure the likely impacts in terms of gross domestic product (GDP), employment and human welfare (see Figure 14). Analysis of the drivers and dynamics affecting the outcome provide valuable insights into how the overall transition process can be shaped to maximise these benefits and reduce the costs of adjustment.

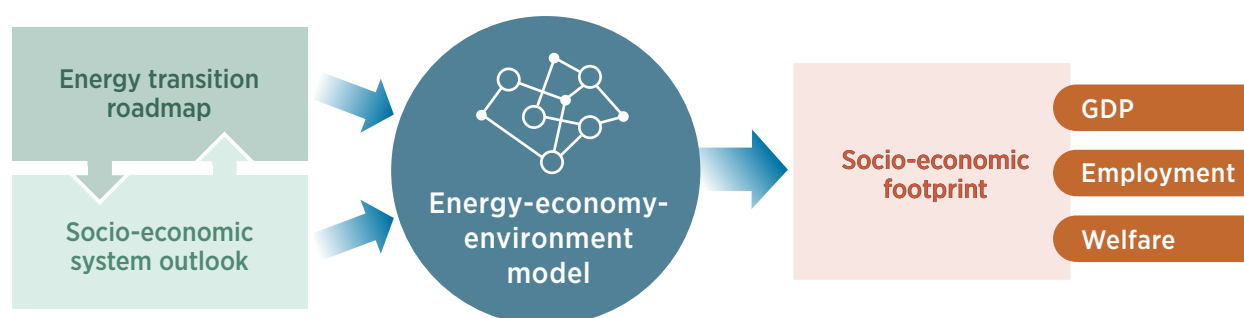
Figure 13. The embedded nature of the energy system



Source: IRENA, 2019d

The power and energy systems are embedded into the wider socio-economic system, which in turn is embedded into the earth and its climate. In order to avoid dysfunctional outcomes, a holistic policy framework is needed to frame and support the transition.

Figure 14. The energy transition and its socio-economic footprint



Note: GDP = gross domestic product.
Source: IRENA, 2018b

Both the energy and socio-economic systems will evolve during the transition, with multiple feedback loops between them. IRENA uses an integrated Energy-Economy-Environment model to evaluate the socio-economic footprint that results from the interactions among different combinations of the energy transition roadmap and the socio-economic outlook.

ECONOMY-WIDE GDP AND EMPLOYMENT IMPACTS

The analysis presented in this section builds on IRENA's body of work, which has focused on measuring the economics and benefits of the energy transition and on assessing renewable energy employment (IRENA, 2019d, 2018d, 2017d, 2017g, 2017h, 2016b; IEA and IRENA, 2017). The analysis delves into macroeconomic variables to present the socio-economic footprint of the REmap roadmap, both at global and regional levels, as deployed within the current socio-economic system⁸.

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

The transition provides socio-economic benefits that go well beyond what GDP



⁸ To perform this analysis, the E3ME energy-economy model from Cambridge Econometrics has been applied. The E3ME is a global macro-econometric model with regional and sectoral resolution that captures the diverse interactions between the energy and economy systems.

can measure. Regarding employment outcomes, beyond global economy employment, the analysis also delves into the energy sector and its components (e.g., renewables, energy efficiency, grids upgrade and energy flexibility). A welfare indicator encompassing economic, social and environmental dimensions is used to quantify the broader transition impacts.

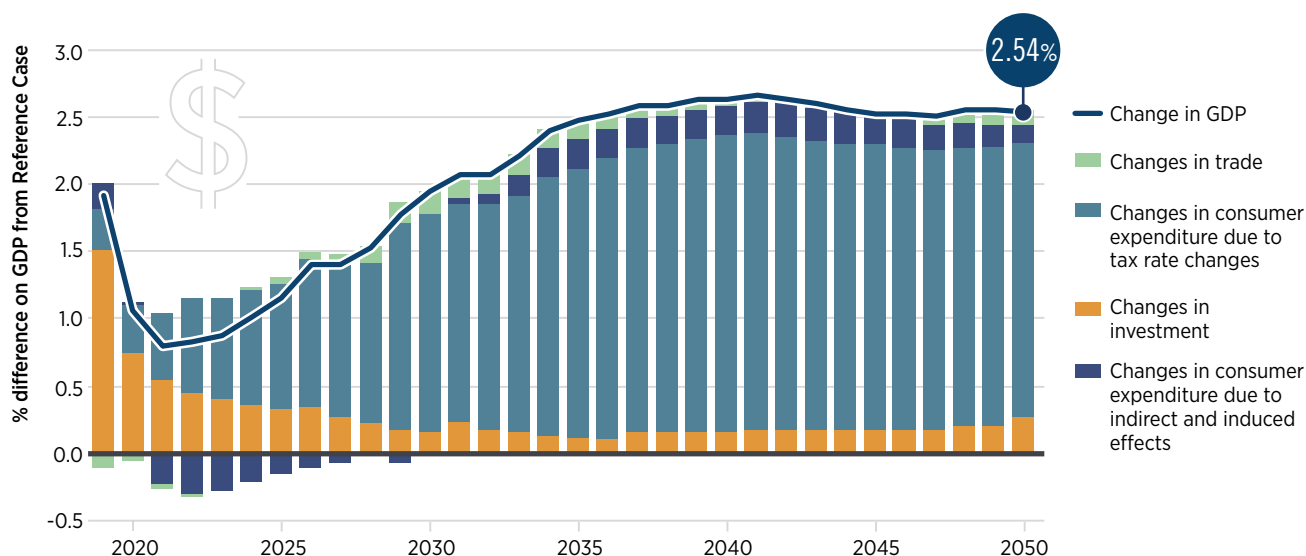
Across the world economy, GDP increases from 2019 to 2050 in both the Reference and REmap cases. However, the energy transition stimulates additional economic activity. Compared to the Reference Case, the REmap Case boosts the GDP by 2.5% in 2050. The CAGR⁹ from 2019 to 2050 increases from 2.4% in the Reference

scenario to 2.5% in the REmap scenario. While this may appear to be a minor difference, the cumulative GDP gain of the REmap Case over the Reference Case from 2019 till 2050 amounts to 2015 USD 99 trillion.

Figure 15 presents the global socio-economic footprint of the REmap energy transition in terms of GDP¹⁰, with a breakdown in terms of the main macroeconomic drivers: investment, trade and changes in consumer expenditure due to tax rate changes, indirect and induced effects.

In the short term, the net positive impact on global GDP is due mainly to a front-loaded investment stimulus in renewable energy generation capacity, energy efficiency, and

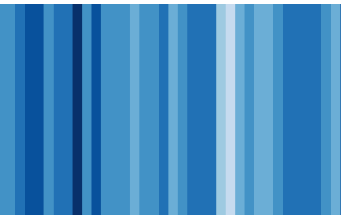
Figure 15. Relative difference of global GDP between the REmap Case and the Reference Case, 2019-2050



To gain insight about the structural elements underpinning the evolution of GDP as a consequence of the interactions between the energy transition and the socio-economic system, the macroeconomic modelling undertaken by IRENA disaggregates the evolution of GDP into four main drivers: Trade, consumer expenditure due to tax rate changes, consumer expenditure due to indirect and induced effects and investment.

⁹ CAGR stands for the Compound Annual Growth Rate. The CAGR is measure of growth over multiple time periods. It can be thought of as the growth rate that gets you from the initial GDP value to the ending GDP value if you assume that the GDP has been growing over the time period with a constant annual growth rate equal to the CAGR.

¹⁰ The indicator used to measure the socio-economic footprint in terms of GDP is the relative increase of GDP from the REmap over the Reference Case, and therefore is evaluated as: $(GDP_{REmap} - GDP_{Reference}) / GDP_{Reference}$.



energy system flexibility to support the transition. The overall impact of this driver gradually fades in importance as time progresses.

Gains in consumer expenditure due to tax rate changes become the dominant factor in the evolution of GDP between 2022 and 2050. This driver captures the impact of the changes in government income due to carbon taxes, fossil fuel phase-out, changes in fossil fuel royalties and other taxes. The model assumes that there is no net change in overall government revenue. Revenue gains/losses are recycled to the population by way of a reduction/increase of income taxes, which drives up/down households' disposable incomes and consumption, and, therefore, GDP is pushed up/down by this driver. In the current REmap footprint analysis, carbon taxes aligned with a 2°C global warming climate goal have been assumed. These carbon taxes and the associated revenue recycling are the main responsible for the GDP impact due to the 'changes in consumer expenditure due to tax rate changes' driver shown in Figure 15.

It should be noted, however, that the positive impacts of increased carbon taxation on GDP¹¹ can hide other negative socio-economic impacts. Increased carbon taxation triggers price increases in energy and other consumption products across the economy. The overall average impact of this price increases can be appreciated in the small and initially negative effect of the induced and indirect driver in GDP (Figure 15), but the lower part of the income distribution can experience a disproportionate share of this impact. Hence, if not accompanied by appropriate policies to distribute the burden, carbon taxes can lead to an increase in inequality and transition barriers. IRENA is currently analysing the distributional aspects of the energy transition to gain insight about how they can be addressed with appropriate

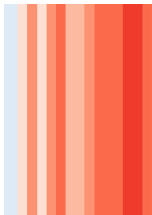
policy to improve the socio-economic impact beyond GDP (IRENA 2020. Forthcoming).

As expected, global trade has a minor impact on the global GDP increase throughout the whole transition, given the intrinsic requirement of global trade being balanced in nominal terms.

Across the world economy, overall employment increases between 2018 and 2050 under both the Reference and REmap cases, with a CAGR of 0.45% and 0.46% respectively.

The employment gains are expected to be less significant than for GDP because additional demand in the global economy also pushes up real wages. The additional wage volume available can be translated either as wage increases for all workers, or as an increase in the number of jobs, or a mix of both. Historical trends show that wage effects tend to dominate, leading to smaller increases in employment than GDP.

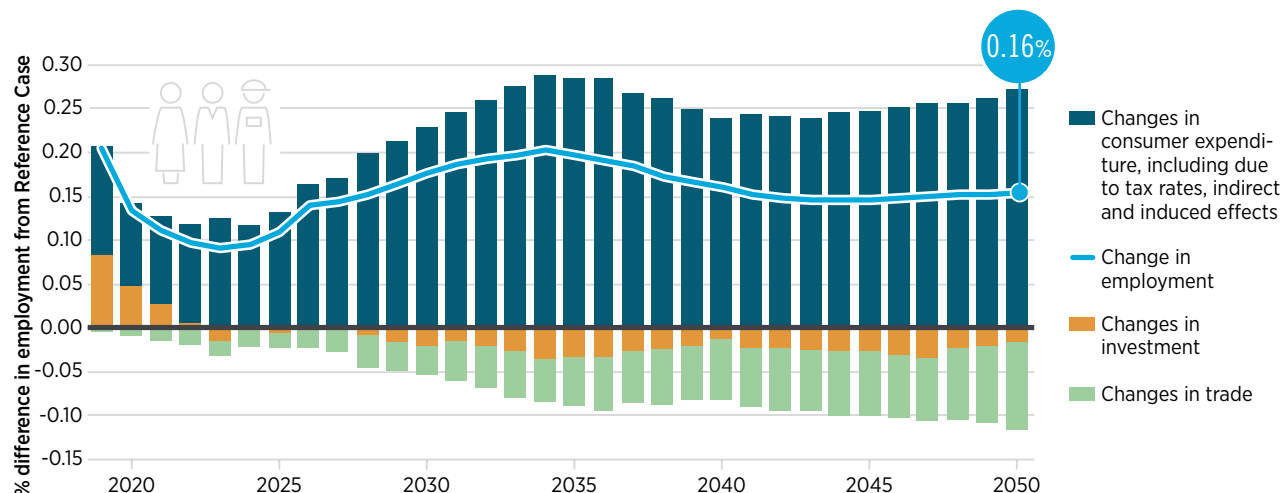
In terms of overall economy's employment Figure 16 shows the evolution of the relative difference of global employment between the REmap Case and the Reference Case. Employment relative differential peaks around 2035 with a 0.20% improvement of the REmap Case over the Reference Case, and then stabilizes around a 0.16% improvement over the Reference Case. After an initial positive impact of the investment driver, this fades out and becomes slightly negative. This behaviour mirrors the front loading of investment (see Figure 15) and the impact of crowding out in other sectors of the economy with higher employment intensities. The positive impact of the 'changes in consumer expenditure'¹² driver dominates the results in the overall economy's employment. The trade driver has a negative impact on the employment footprint indicator, initially associated to changes in net trade in fuels, but reinforced after 2035 by changes in non-energy trade.



¹¹ Through reduced income taxation due to government revenue balancing.

¹² Consumer expenditure includes the net impacts of tax rates and indirect and induced effects

Figure 16. Relative difference of global employment between the REmap Case and the Reference Case, 2019-2050



While overall employment impacts of the REmap transition in the whole economy are not very significant, those in the energy sector are very positive, with new jobs associated with the transition (renewable generation, energy efficiency and energy flexibility), significantly outweighing the lost jobs in the fossil fuel sector (IRENA, 2019d, 2018a, 2016b) (IEA and IRENA, 2017). If the energy-related jobs are increasing significantly while the number of jobs in the overall economy are barely increasing, this implies that jobs in some non-energy related sectors are declining - partly due to the crowding-out effect.

These employment trends call for widening the conceptual framework for just transition considerations and clearly require addressing temporal, spatial and educational mismatches between new transition-related jobs and job losses within the energy sector and in other sectors of the economy. Therefore, specific policies will need to address these mismatches to ensure that transition outcomes are just both in the energy sector and beyond. The imperative is to frame transition policies in a holistic way across the whole socio-economic system

To gain insight about the structural elements underpinning the evolution of Employment as a consequence of the interactions between the energy transition and the socio-economic system, the macroeconomic modelling undertaken by IRENA disaggregates the evolution of Employment into three main drivers: Trade, consumer expenditure (including tax rates and indirect and induced effects) and investment.

to benefit from synergies and address conflicts at the source.

It should be noted that the main socio-economic results presented (GDP and jobs) do not capture the impacts of climate change, the very driver of the energy transition on the economy. The macroeconomic model assumes that economic activity is not influenced by climate change, and hence both the Reference and REmap cases are left to progress along their macroeconomic pathways. IRENA has made a first attempt to quantify the impacts of climate damage on the GDP socio-economic indicator.

CLIMATE DAMAGES AND ITS IMPACT ON GDP

The literature suggests that very important impacts from climate change can be expected on the performance of the socio-economic system both in terms of reducing global GDP and increasing inequality:

- For the end of the century (year 2100) global GDP reductions are estimated at around 20% for a 2°C global warming and 35% for a 5°C global warming are reported¹³ (Burke *et al*, 2018).
- Climate damages will lead to increased inequality because much higher impacts can be expected in warmer regions¹⁴, which often correspond to poorer countries (Burke *et al*, 2015).

Climate damages may have a deeper impact than what is suggested by externality evaluations, as they can affect the very operation of the socio-economic system, with multiple macroeconomic and social feedback processes. The integration of climate damages into macroeconomic models allows to capture feedback effects and better reflect the distribution of damages at sectoral and regional level.

IRENA has incorporated into its macro-economic modelling a climate damage methodology based in (Burke *et al*, 2015) and (Burke *et al*, 2018) (see Box 2). This is an econometric and empirically-based methodology, consistent with the econometric nature of the E3ME macroeconomic model used by IRENA for the socio-economic footprint analysis, which captures the temperature-related effects of climate change on economic productivity. The climate damages obtained with this

methodology have to be understood as a conservative estimate of the potential climate damages on the economy (see Box 3).

Figure 17 presents the effect, in terms of the GDP indicator (relative GDP increase of the REmap Case over the Reference Case), of including climate damages in the REmap socio-economic footprint analysis. As it can be seen, the impact of climate damages is very important, and it increases over time with cumulative GHG emissions.¹⁵ In year 2050 the relative increase of REmap GDP over Reference GDP goes from 2.5% when no climate damages are accounted for, up to 5.3% when climate damages are included in the macroeconomic modelling. However, this significant improvement in the *relative* GDP performance of the REmap over the Reference Case has to be taken with a note of caution, because it hides a very important deterioration of the REmap GDP performance when climate damages are factored into the macroeconomic analysis¹⁶.

It is important to understand that the *improvement* in the GDP socio-economic footprint indicator when climate damages are factored into the macroeconomic analysis occurs despite a *decrease* of GDP both in the Reference and REmap cases. Climate damages decrease GDP for both the Reference and REmap cases because both pathways lead to a significant amount of cumulative CO₂ emissions. However, the cumulative CO₂ emissions from REmap are significantly lower than those from the Reference Case, and hence the climate damage in the Reference Case is higher than in the REmap Case.

¹³ It should be noted that a 20% reduction in GDP for 2°C global warming is around 10 times higher than the increase of GDP of the REmap case over the Reference case that results from the socio-economic footprint analysis of the REmap energy transition (also aligned with a 2°C global warming).

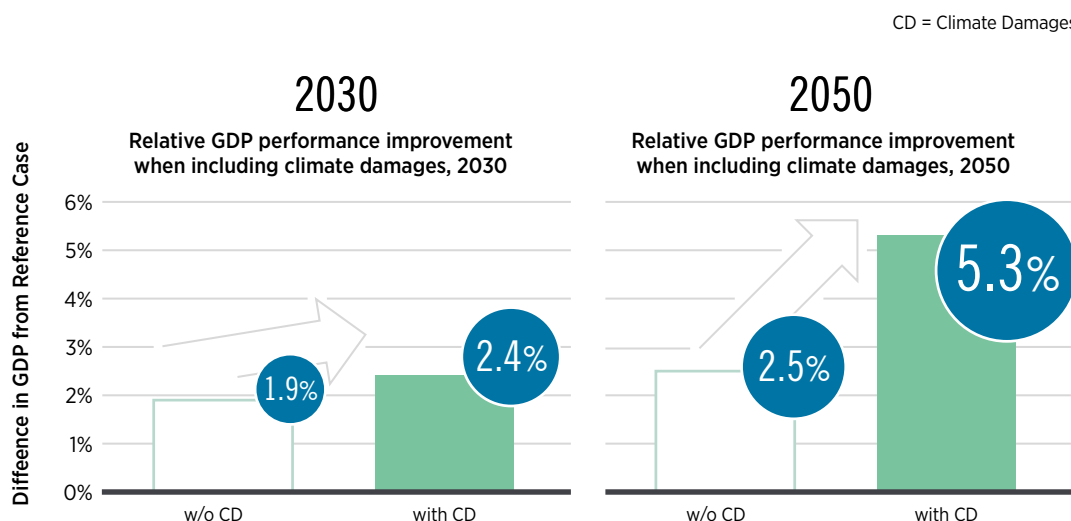
¹⁴ This is due to the non-linearity with temperature of the climate damage function, which can produce very high negative impacts in regions of the world that currently have warmer temperatures while simultaneously producing positive impacts in regions of the world that currently have cooler temperatures.

¹⁵ This fact strongly supports the importance of extending the socio-economic footprint analysis up to 2100 – year for which the current climate goals in terms of global warming are set. Other reasons supporting this extension are allowing the energy transition to be completed within the analysis period and capturing the implications of convergence or its absence into the socio-economic footprint. Convergence here makes reference to the overall socio-economic transition process aiming at reducing inequalities (in income, wealth, energy use...) both between and within countries.

¹⁶ This fact calls for the need to increase the energy transition ambition as much as possible.

Figure 17. Impact of climate damages on the GDP indicator used for the socio-economic footprint analysis

The indicator used for the socio-economic footprint analysis is the relative difference between the REmap Case GDP and Reference Case GDP: $(GDP_{REmap} - GDP_{Reference})/GDP_{Reference}$



The incorporation of climate damages into the socio-economic footprint analysis leads to a significant increase of the indicator used for the GDP (relative increase of the REmap over the Reference), which becomes more important over time as the cumulative CO₂ emissions increase.

The upper graph in Figure 18 presents per capita GDPs with and without climate damages.¹⁷ Clear green bars represent the per capita GDP without taking into account climate damages, while dark green bars represent the per capita GDP once climate damages are factored in. As it can be seen both REmap and Reference cases experience a significant reduction in GDP when climate damages are included in the macroeconomic modelling. To better understand these reductions, the lower graph in Figure 18 presents the percentage

reduction in GDP¹⁸ when climate damages are included, showing how important¹⁹ are the GDP reductions attributable to climate change.

In 2050, the Reference Case experiences a 15.5% reduction in GDP, while the REmap Case sees a 13.2% reduction. The fact that the reduction in GDP due to climate damages is higher for the Reference Case than for the REmap Case is what leads to the increase in the socio-economic footprint indicator for GDP²⁰ presented in Figure 17.

¹⁷ When comparing the evolution between 2030 and 2050, both the Reference and REmap cases experience a significant growth in per capita GDP, although in the case with climate damages growth is reduced due to the higher impact of climate damages in 2050 compared to that of 2030.

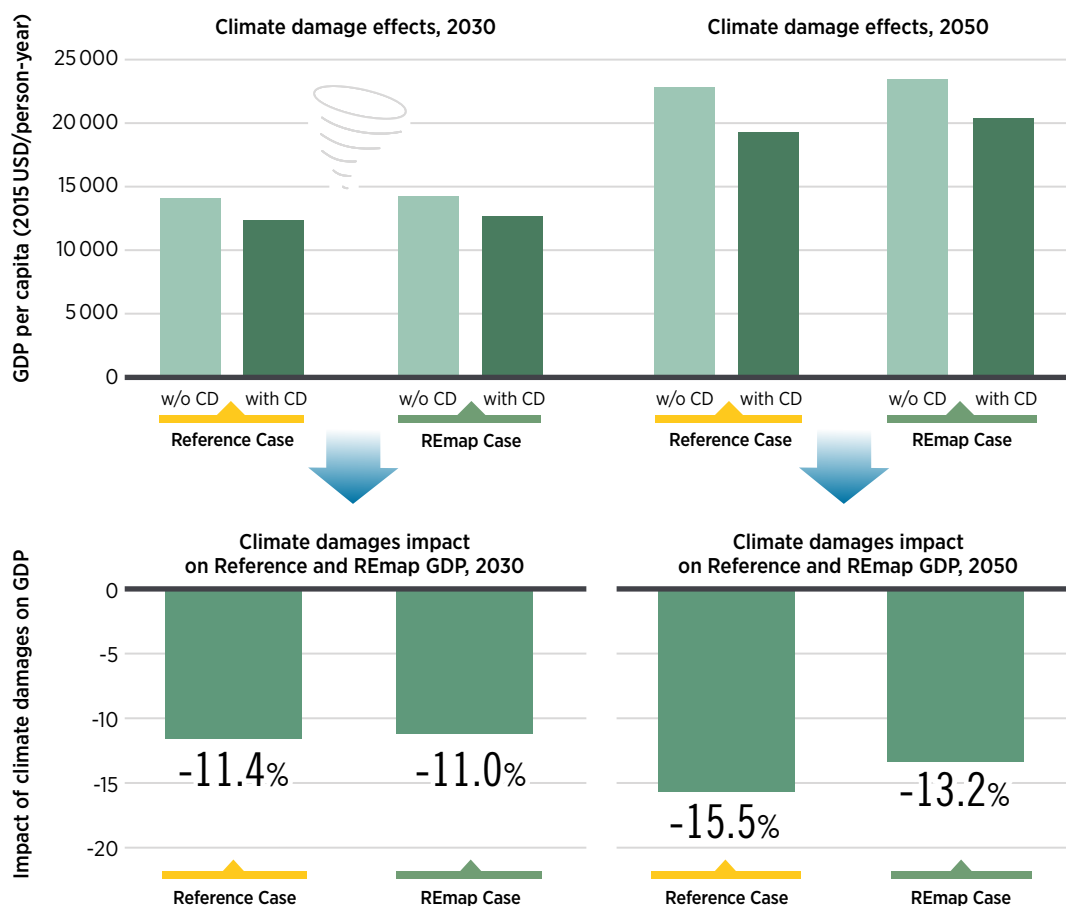
¹⁸ This is evaluated for each the Reference and REmap cases as: $(GDP_{with\ CD} - GDP_{w/o\ CD}) / GDP_{w/o\ CD}$

¹⁹ To better appreciate the magnitude of this importance, the GDP reductions due to climate damages should be compared with the GDP increases of the REmap over the Reference Case that we documented in the former section. For instance, in year 2050 the REmap provides a 2.5% GDP increase over the Reference Case, but climate damages produce a 13.2% decrease in REmap's GDP.

²⁰ The socio-economic footprint indicator for GDP is the relative increase of REmap over the Reference Case and is evaluated as: $(GDP_{REmap} - GDP_{Reference})/GDP_{Reference}$.

Figure 18. Impact of climate damages on GDP results

Per capita GDP evaluated without (w/o CD) and with (with CD) climate damages, as well as the relative impact of climate damages in each case.



The incorporation of climate damages into the macroeconomic model has a very important impact on the GDP results both for the REmap Case and the Reference Case, which increases over time as cumulative GHG emissions increase. The CO₂ emissions mitigation provided by the REmap energy transition leads to a lower climate damage impact than the one experienced by the Reference Case.

Box 2. EVALUATING THE IMPACT OF CLIMATE DAMAGES IN THE MACROECONOMIC PERFORMANCE.

The methodology used to incorporate climate damages into E3ME macroeconomic modeling is based on (Burke M., *et al*, 2015) and (Burke M., *et al*, 2018).

The implemented methodology consists of an econometric approach to derive a non-linear damage function that maps temperature changes to economic losses, whereby macro-level data is used to estimate the long run relationship between temperature and economic productivity (empirical damage function).

This macro-approach provides an appropriate way of capturing the net effect from the many impacts and feedbacks that climate change produces within the economy, leading to a significantly more comprehensive quantification of climate damage effects than what can be obtained through the quantification and aggregation of micro-level climate change externalities in bottom-up approaches.

The climate damages methodology, based on empirical data and using statistical procedures to control for other variables and country specific contexts, tracks the effects of temperature in economic productivity, in such a way that the overall impact of higher average temperatures because of climate change (decreased labour and capital productivity in each of the economic sectors, effects on human health and mortality...) can be quantified.

To estimate the historical relationship between temperature and GDP, (Burke M., *et al* 2015, 2018) use annual measurements of average temperature and growth in GDP per capita from 165 countries over the years 1960–2010.

The statistical and econometric analysis of the available data “deconvolves economic growth to account for: all constant differences between countries, for example, culture or history; all common contemporaneous shocks, for example, global price changes or technological innovations; country-specific quadratic trends in growth rates, which may arise, for example, from changing political institutions or economic policies; and the possibly non-linear effects of annual average temperature and rainfall”, “In this framework, each country is allowed its own level and nonlinear trend in growth, and the impact of temperature on growth is identified from within-country deviations from this trend”. (Burke M., *et al* 2015).



Box 3. WHAT DOES THE APPLIED CLIMATE DAMAGE METHODOLOGY INCLUDE AND WHAT NOT?

The implemented climate damage technology captures all the temperature-related (or for which historical temperature has been a proxy) effects of climate change on economic productivity, with a consistent formulation based on empirical data and a robust statistical and econometric treatment, allowing for non-linearity in the response to temperature changes. The methodology estimates climate damages significantly higher than those considered in most Integrated Assessment Models (Burke *et al* 2015). The results obtained with this methodology can, however, be considered conservative, because there are several ways through which climate change can negatively impact the economy that are not captured by it:

- Sea level rise and increased incidence of extreme weather events (flooding, draughts, tropical cyclones, wildfires...).
- Disrupted trade and modified trade dynamics based on modified power positions, where regions with higher damages on GDP (Global South) experience losses in trade balance, and winners (Global North) use the advantageous situation to impose trade agreements.
- Social conflict effects associated to disruption and increasing inequality.
- Surpassing climate tipping points, which is likely for global warming above 1.5°C.
- Cross-country spillovers associated to climate change that would produce higher economic impacts (for example, supply chain interruptions/alterations, trade effects...)
- Structural climate impacts not experienced in the past.
- Rate of change effects. Temperature change happening at a much higher rate than historic temperature changes challenges the capability of adaption and opens the door to disruption. This includes for example the effects of relocating economic activities in short time frames.
- Although includes the impact of temperature in the changes of capital productivity, it does not directly address the impacts on the different dimensions of capital (physical, social, human and natural).
- The current formulation caps the damage function at the maximum observed temperature, while its extrapolation beyond that point would lead to higher damages. This leads to conservative results mainly in hot and poor countries, and therefore the inequality increase linked to climate change could be higher than the one currently predicted.
- The current formulation assumes a negligible effect of non-CO₂ GHG emissions on global warming from 2019 onwards.

ACTION NEEDED NOW

This report makes clear that an energy transition is urgently required, and that renewable energy, energy efficiency and electrification are the three cornerstones of that transition. Technologies for these pillars are available today, are deployable at a large scale quickly and are cost-competitive.

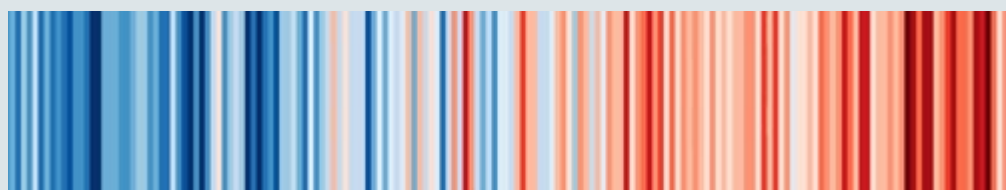
The Paris Agreement was signed in 2015. Since then energy-related CO₂ emissions have risen by around 4%. The coming years are critical: there is a need for a leap in national collective ambition levels. The revisions of the NDCs in 2020 in combination with Long-term Strategies must yield a convincing outcome for an energy transition that puts the world on a global pathway to reduced emissions, despite differing views on the mitigation measures needed and the rapid evolution of renewable technologies. The following section outlines some of the key actions that are needed now.

The power sector needs to be transformed to accommodate growing shares of variable renewables

- Develop power systems that provide a high level of technical **flexibility** (through flexible supply, transmission, distribution, storage, demand response, power-to-X, EVs, *etc.*,) complemented by operational flexibility.
- Better **market signals** are needed to enable flexibility resources to come into play to cope with the uncertainty and variability of VRE generation. Examples include real-time variable pricing and shorter trading intervals.
- Power markets will need to be redesigned to enable the **optimal investments** for systems with high levels of VRE and enable sector coupling.

Digitalisation is a key enabler to amplify the energy transformation

- Smart innovations can be turned into smart solutions using a range of **digital technologies**. Digital innovations (such as artificial intelligence, the Internet of Things, blockchain, *etc.*,) are increasing and could greatly impact power systems in many different, positive ways.
- As the power sector begins to see the share of VRE rise, the overall flexibility of the system will need to increase. A large potential form of flexibility will be being able to **shift electricity demand** to times when electricity is in large supply; smart meters, digital networks and interconnected appliances can help to promote these types of shifts.



Annual temperatures in Toronto from 1841-2017

The colour scale goes from 5.5°C (dark blue) to 11.0°C (dark red)



Accelerating the electrification of the transport and heating sectors is crucial for the next stage of energy transformation

- **EV charging infrastructure** must be supported. With a growing number of EVs on the road, charging infrastructure incentives should be designed to kickstart these markets, following already established good practices.
- **Alternative heating technologies**, such as heat pumps in industries (for low-temperature applications) and buildings, should be promoted.
- The **electricity and end-use sectors** must be coupled. Electrification strategies must be planned carefully and with consideration of wider societal changes. For instance, smart charging of EVs can improve the flexibility of power systems and is crucial to enable optimal integration of VRE while avoiding network congestion.

Hydrogen produced from renewable electricity could help to reduce fossil-fuel reliance

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

Supply chains are key to meet growing demand for sustainable bioenergy

- **Bioenergy** must be produced in ways that are environmentally, socially and economically sustainable. There is a very large potential to produce bioenergy cost-effectively on existing farmland and grassland, without encroaching upon rainforests, and in addition to growing food requirements.
- **Biomass-based industries** that generate ready-to-use biomass residues – such as pulp and paper, lumber and timber, and food – are fundamental in the transition.
- In sectors such as aviation, shipping and long-haul road transport, **biofuels** might be the main or only option for decarbonisation for years to come. Targeted attention and specific policies must be devoted to these sectors and to the development of advanced biofuels and their related biofuel supply chains.



Decarbonising the global energy system requires swift and decisive policy action

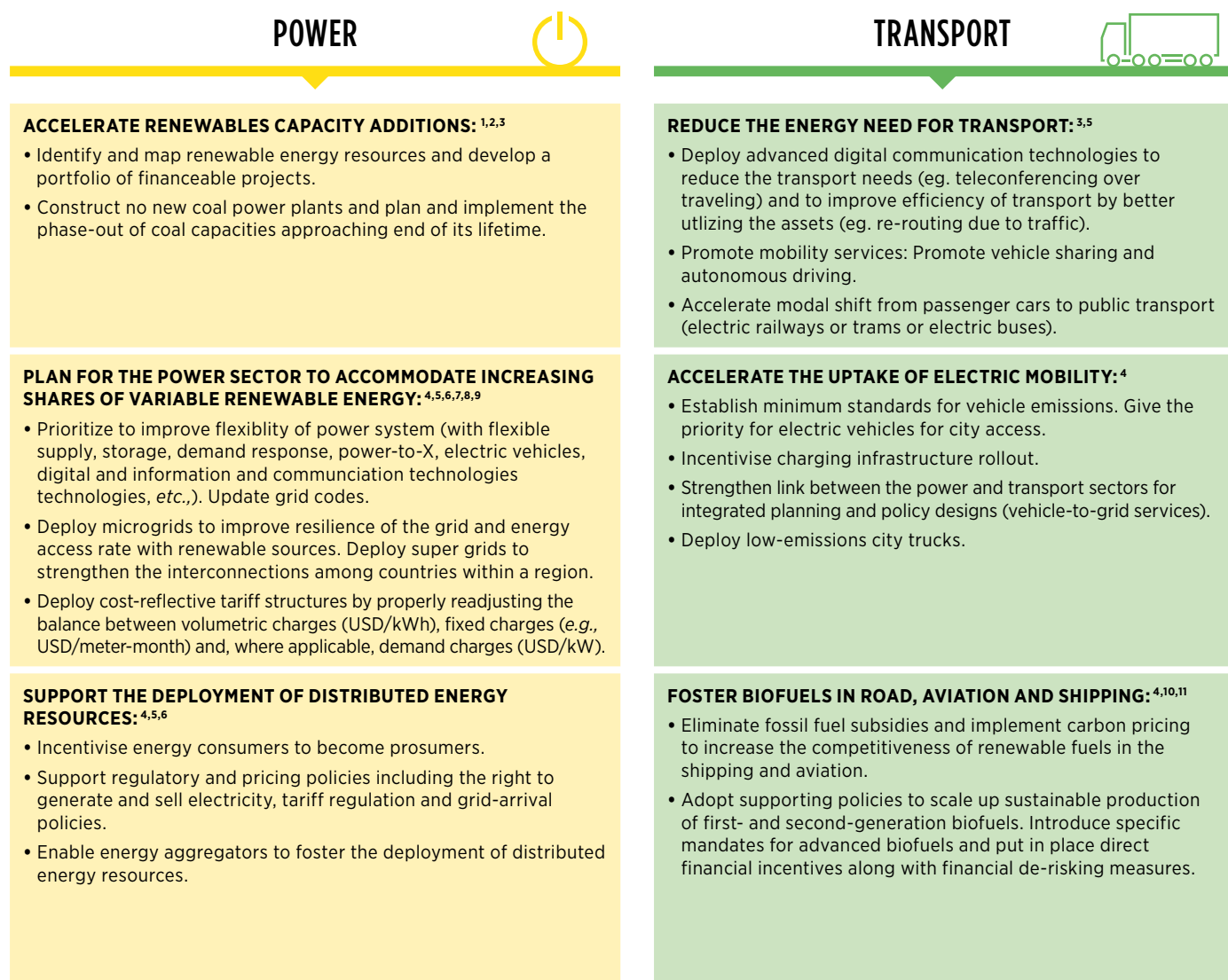
- Policy makers need to establish **long-term energy planning strategies**, define targets and adapt policies and regulations that promote and shape a decarbonised energy system.
- There is general agreement that reducing emissions in the energy sector is key, and that renewable energy and energy efficiency form the backbone of this effort. However, there needs to be better alignment and **co-ordination between energy and climate policies**. Setting a long-term strategy for the energy transition that considers both climate and energy needs is critical, considering action plans in the power sector and in each end-use sector (couple with the SDGs and the NDCs).
- Policies should create the right conditions for **investments** not only in energy efficiency and renewable energy supply, but also in key enabling infrastructure such as grids, EV charging, storage, smart meters *etc.*,
- Close co-operation between the **public and private sectors** will be key. The private sector can be a key driver for the energy transformation. For instance by increasing demand for renewables through corporate clean energy procurement, investment in the roll-out of EV charging infrastructure, *etc.* Therefore, aligning public policies with private sector initiatives is important.
- It is important to promote systemic innovation by creating a regulatory environment that enables smarter energy systems through **digitalisation** (eg., artificial intelligence, the Internet of Things, blockchain), to promote the coupling of sectors through greater electrification and to embrace decentralisation trends. This innovation needs to be expanded beyond technology and into markets, regulations, new operational practices in the power sector and new business models.
- **Circular economy** practices can drive deep, and readily realisable, reductions in energy demand and emissions. Reusing, recycling and reducing the use of water, metals, resources, residues and raw materials in general, should be amplified.
- Energy tariffs should reflect the costs and **avoid inefficient subsidies**. Hidden costs and negative externalities should be internalised. Regulations should allow variations or adaptations over time and space, such as tariffs that vary depending on time of use.
- **Financing schemes** for accelerating deployment of renewables and energy efficiency measures for energy demand and supply projects should be promoted. Potential stranded assets should be internalised in overall risks assessment.
- The G20 forum, the SDGs and the review of NDCs in 2020 provide opportunities to drive action and to couple long-term energy and climate strategies. However, **ambitious action at the national and sub-national levels**, particularly in cities and the private sector, will also be important for success, since regions and countries can act and drive action themselves.

Actions in the power, industry, buildings and transport sectors are essential to realise the global energy transformation by 2050. An overview of major actions at the sector level are listed in Figure 19.

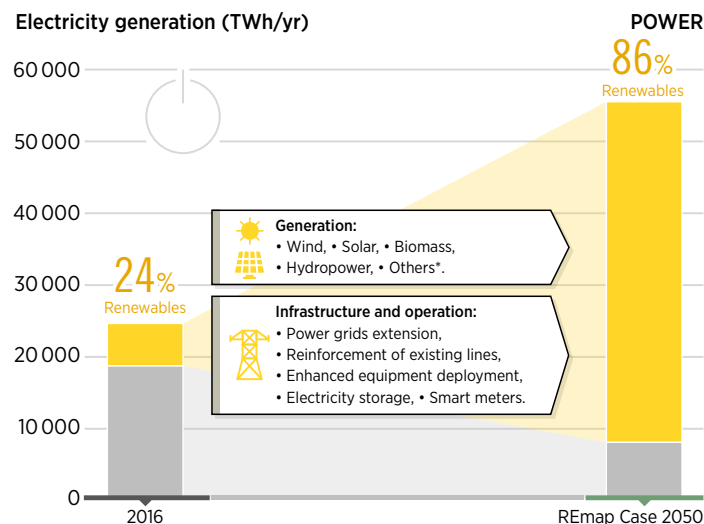


Figure 19. Implementation of sector-level actions from now is highly essential to effectively transform the global energy system

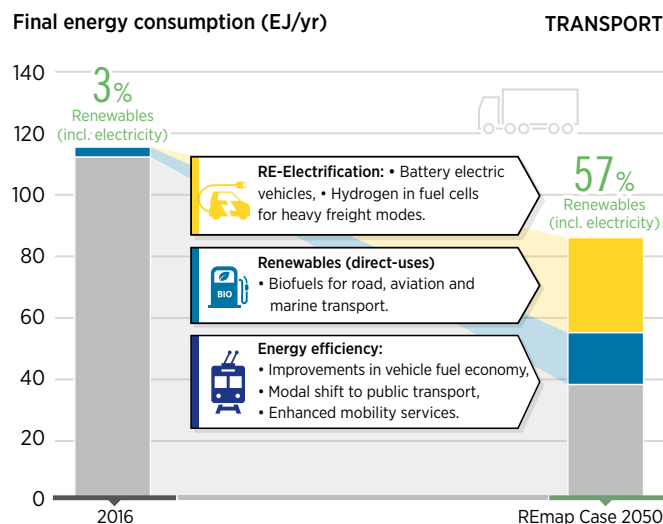
Overview of key policy actions to be implemented in the power, transport, industry and buildings sector.



Electricity generation (TWh/yr)



Final energy consumption (EJ/yr)



Sources: 1) (IRENA, n.d.); 2) (IRENA, n.d.); 3) IRENA (2018a); 4) IRENA, IEA and REN21 (2018); 5) IRENA (2019b); 6) (IRENA, forthcoming); 7) IRENA (2018g); 8) IRENA (2018b); 9) IRENA (2016b); 10) IRENA (2016a); 11) (IRENA, 2017b, 2015); 12) IRENA (2018e); 13) (IRENA, 2018i); 14) IEA (2018e).

INDUSTRY

REDUCE ENERGY CONSUMPTION IN INDUSTRIES:³

- Promote actions towards circular economy (material recycling, waste management, improvements in materials efficiency and structural changes such as reusing and recycling).
- Incentivise and adopt best available technologies (BAT) and efficiency standards.

ENABLE CORPORATE SOURCING OF RENEWABLES:¹²

- Support a credible and transparent system for certification and tracking of renewable energy attributes.
- Consider an energy market structure that allows for direct trade between companies of all sizes and renewable energy developers – such as through PPAs.
- Work with utilities or electric suppliers to provide green corporate procurement options.
- Empower companies to engage in direct investment for self-generation.

ACCELERATE THE DEPLOYMENT OF LOW-CARBON TECHNOLOGIES IN INDUSTRIAL PROCESS HEATING:^{3,4,13}

- Remove existing barriers and incentivise low-carbon heating technologies deployment: Solar thermal heating/modern bioenergy and heat pumps.
- Support emerging technologies in biomass and hydrogen. Use renewable-produced hydrogen to replace fossil fuel-based feedstocks and process heat (e.g., iron and steel sub-sectors, ammonia production).
- Implement appropriate carbon pricing in line with the real costs of the externalities and the elimination of existing subsidies for carbon-intensive fuels (where those still exist).

BUILDINGS

REDUCE ENERGY CONSUMPTION IN BUILDINGS:^{3,4,14}

- Establish and improve energy efficiency building codes and standards (incl. appliances (eg. air conditioners), lighting (eg. LED lights) and equipment (eg. efficient boilers)).
- Adopt programmes for retrofitting/renovation including financing schemes.
- Align renewable heat and energy efficiency policies to leverage synergies and to accelerate the pace of energy efficiency improvements.

SUPPORT AND FOSTER THE DEPLOYMENT OF DISTRIBUTED ENERGY RESOURCES:^{3,4,5,6}

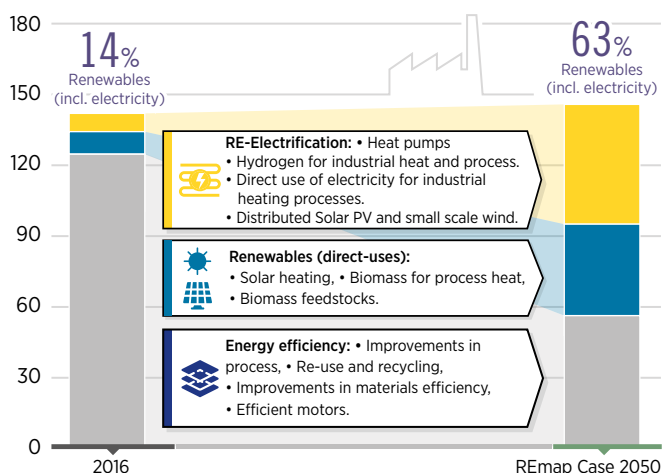
- Remove regulatory barriers for prosumers that restrict them from taking an active role in the energy system transformation. Capitalise on smart-homes and digitalisation to allow demand management.
- Promote community ownership models and innovative financing schemes.
- Accelerate rollout of smart meters.

SCALEUP RENEWABLE SHARE UPTAKE IN THE BUILDINGS SECTOR:^{3,4}

- Promote low-carbon heating technologies: heat pumps, solar heating, modern bioenergy for heating). Apply these renewable technologies for district heating.
- Establish a long term strategy for heat decarbonisation.
- Incentivise renewable based cooling solutions.
- Phase out traditional biomass as cooking fuel and replace with clean and efficient cookstoves (biogas, modern solid biomass and electricity).

Final energy consumption (EJ/yr)

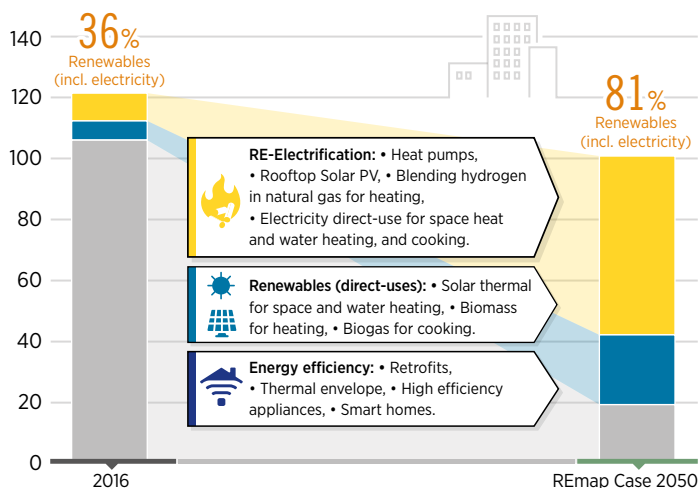
INDUSTRY



■ = Renewable electricity; ■ = Renewables (Direct-use and DH); ■ = Non-renewables

Final energy consumption (EJ/yr)

BUILDINGS



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