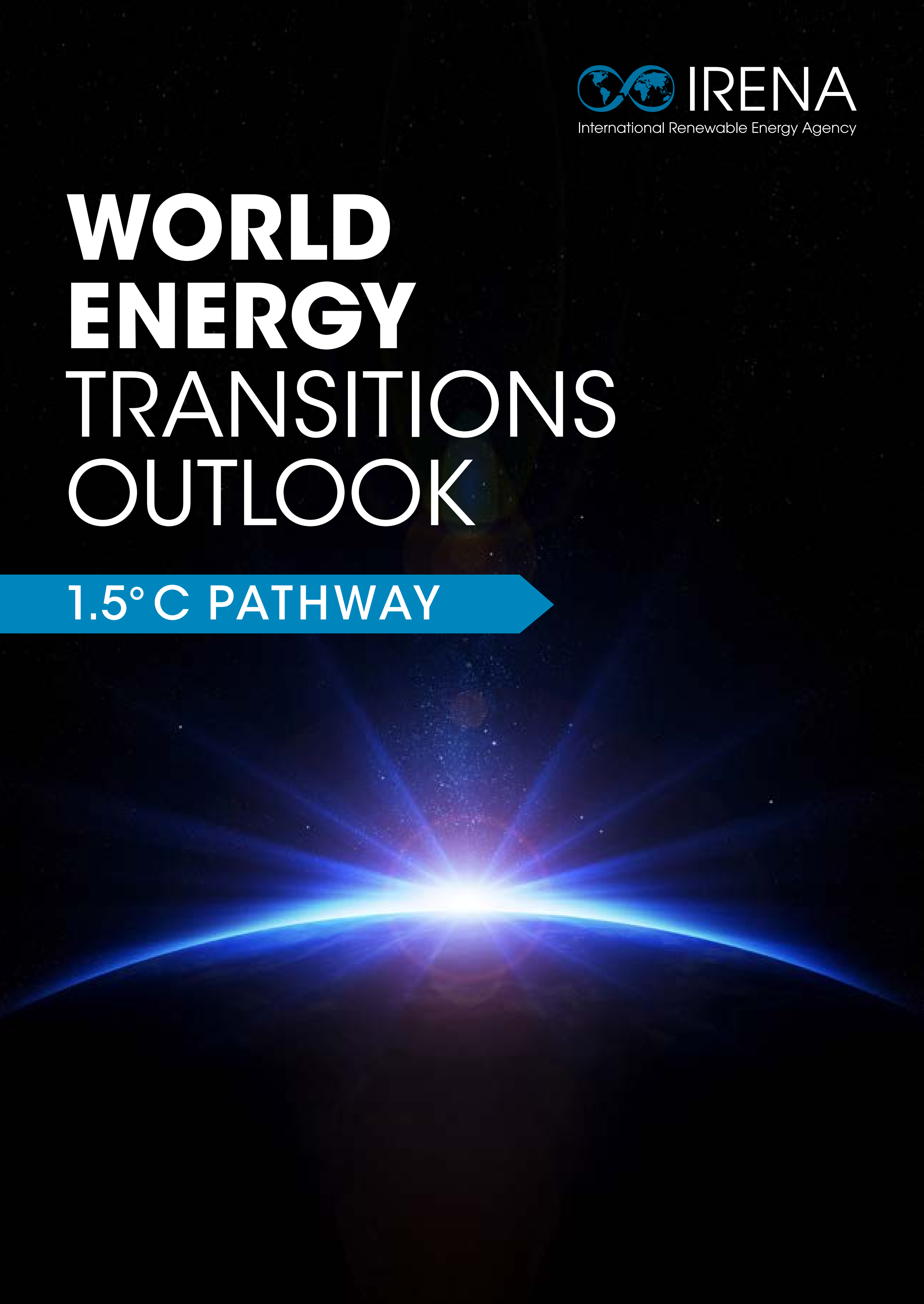

WORLD ENERGY TRANSITIONS OUTLOOK

1.5°C PATHWAY

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ABOUT IRENA

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

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WORLD ENERGY TRANSITIONS OUTLOOK

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FOREWORD

We have no time. The window is closing and the pathway to a net zero future is narrowing. This was the message I delivered plainly and unambiguously when we released the *World Energy Transitions Outlook* preview at the Berlin Energy Transitions Dialogue earlier this year. Science is clear: 45% of global greenhouse gas emissions from 2010 levels must be reduced by 2030. Unfortunately, the recent trends show that the gap between where we are and where we should be is widening. We are on the wrong path, and we need to change the course now.

The choices we make in the coming years will have a far-reaching impact. They could bring us on a path toward the goals we set out in 2015 when we adopted the highly consequential international agreements on sustainable development and climate change. Or they could take us in the opposite direction to further warming, with profound and irreversible economic and humanitarian consequences.

It is unwise to make predictions or pre-empt outcomes at uncertain times. But several trends are shaping an unfolding energy transition and giving an indication of its direction. First, the costs of renewable technologies have plummeted to the point that new fossil-based electricity is no longer an attractive option. Second, the progress in the power sector is spilling over to end uses, allowing a re-imagining of possibilities with the abundance of renewable options at hand. Third, a consensus has formed that an energy transition grounded in renewable sources of energy and efficient technologies is the only way to give us a fighting chance of limiting global warming by 2050 to 1.5°C. Only a few years ago, the renewables-centred approach espoused by IRENA was considered too progressive, idealistic or even unrealistic. Today, our vision has become mainstream, and accepted as the only realistic option for a climate-safe world. And this is reflected in the growing number of commitments to net zero strategies by countries in all corners of the world, creating unprecedented political momentum for a transformative change.

IRENA's *World Energy Transitions Outlook* outlines the avenues to take us out of the climate crisis toward a resilient and more equitable world. It clearly shows the options we have today and what gaps need to be filled. The analysis and options presented prioritise existing emission-reduction solutions and those with the highest chance to become viable in the coming years. It does not bet on unproven technologies or pending inventions but encourages much-needed innovation to perfect and advance the fastest path to emission reduction.

The Outlook offers a compelling path for decarbonising all energy uses, with electrification and energy efficiency as primary drivers, enabled by renewables, green hydrogen and sustainable modern bioenergy. But a scenario and its assumptions, however rigorous and comprehensive, are only an instrument to inform policy making. To translate this vision of the energy future into reality, we need to transcend the limits of the existing infrastructure created for the fuels of the past. And these decisions are not made in a vacuum. Economic and human development goals, environmental concerns, and financial avenues must all be reconciled.

It is in this context that IRENA brings its unique value.

The Outlook shows that, when we look beyond the narrow confines of energy supply, a renewables-based transition unlocks a range of valuable benefits. The Outlook thus presents the policy frameworks necessary to advance a transition that is just and inclusive. It provides an improved understanding of structural changes and offers a quantitative framework for impacts such as gross domestic product (GDP), employment and welfare. The report also examines funding structures to show the necessary shift in capital markets.

And this knowledge provides the basis for IRENA to support countries in realising their priorities and turning their strategies into action. With our 164 Members, we see how collective action can drive progress worldwide and where overarching needs and gaps may exist.

This global reach is what gives the Agency the credibility - and privilege - to support international co-operation across the gamut of energy transition issues to help countries learn from each other and tap into the vast expertise of the Agency. And we are actively working with partners, including the private sector, to provide a dynamic platform that drives action, foresighted planning, holistic policy making and investment at scale.

The demands of our time are great and full of uncertainty. We are entering a new era of change, one in which energy transformation will drive economic transformation. This change is bringing unprecedented new possibilities to revitalise economies and lift people out of poverty. But the task ahead is daunting. I hope that this Outlook provides a fresh view on how to turn today's energy problems into tomorrow's solutions.

Our shared future will only be bright if we move together, taking everyone along towards a more resilient, equal, and just world.

Francesco La Camera
Director-General, IRENA

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EXECUTIVE SUMMARY

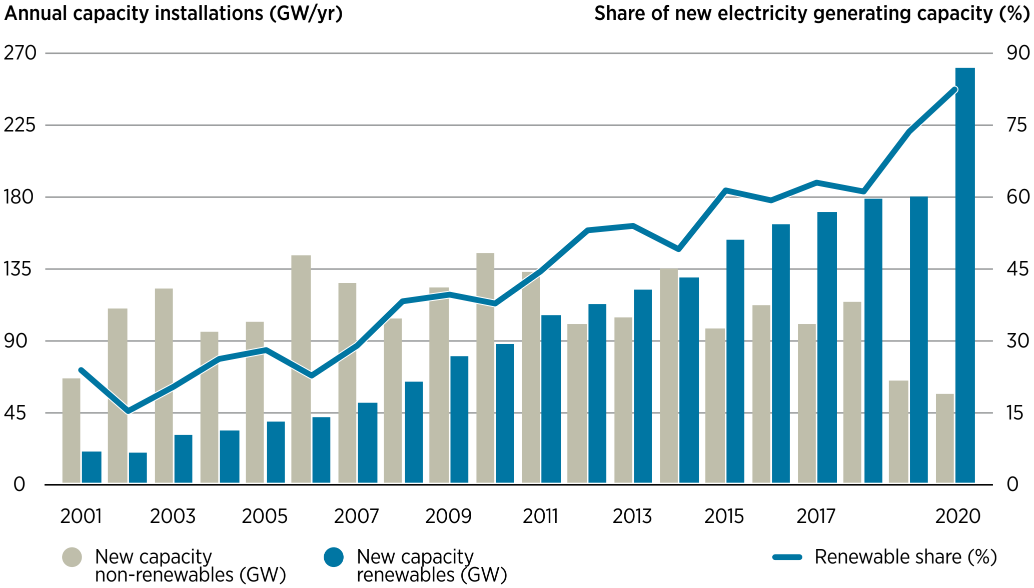
Where are we in the energy transition?

The energy sector, known for its slow pace of change, is undergoing a dynamic transition. The imperatives of climate change, energy poverty and energy security to underpin development and industrial strategy have made the widespread adoption of renewables and related technologies an essential solution. Policy drivers, technology developments and international co-operation have moved these technologies from niche to mainstream, especially in the past decade. Even in the face of the turmoil caused by the COVID-19 pandemic, renewables-based systems demonstrated remarkable resilience, showing technical reliability of renewables-based electricity system with high share of solar and wind.

A consensus has formed that an energy transition grounded in renewable sources and technologies that increases efficiency and conservation is the only way to give us a fighting chance of limiting global warming to 1.5°C by 2050. Only a few years ago, the renewables-centred approach espoused by IRENA was considered idealistic. Today, even some of the most conservative energy players have realised it as the only realistic option for a climate-safe world. Such a profound and pervasive shift of views is rooted in undeniable evidence, not only of the world's grave problems, but also of trends in technology, policy and markets that have been reshaping the energy sector for over a decade.

For the past seven years, more renewable power was added to the grid annually than fossil fuels and nuclear combined. Renewable power technologies now dominate the global market for new electricity generation capacity, as they have become the cheapest sources of electricity in many markets. A record level of 260 gigawatts (GW) of renewables-based generation capacity was added globally in 2020, more than four times the capacity added from other sources (IRENA, 2021a). This a promising trajectory for rapid decarbonisation of the power sector.

FIGURE S.1 **Share of capacity, 2001-2020**

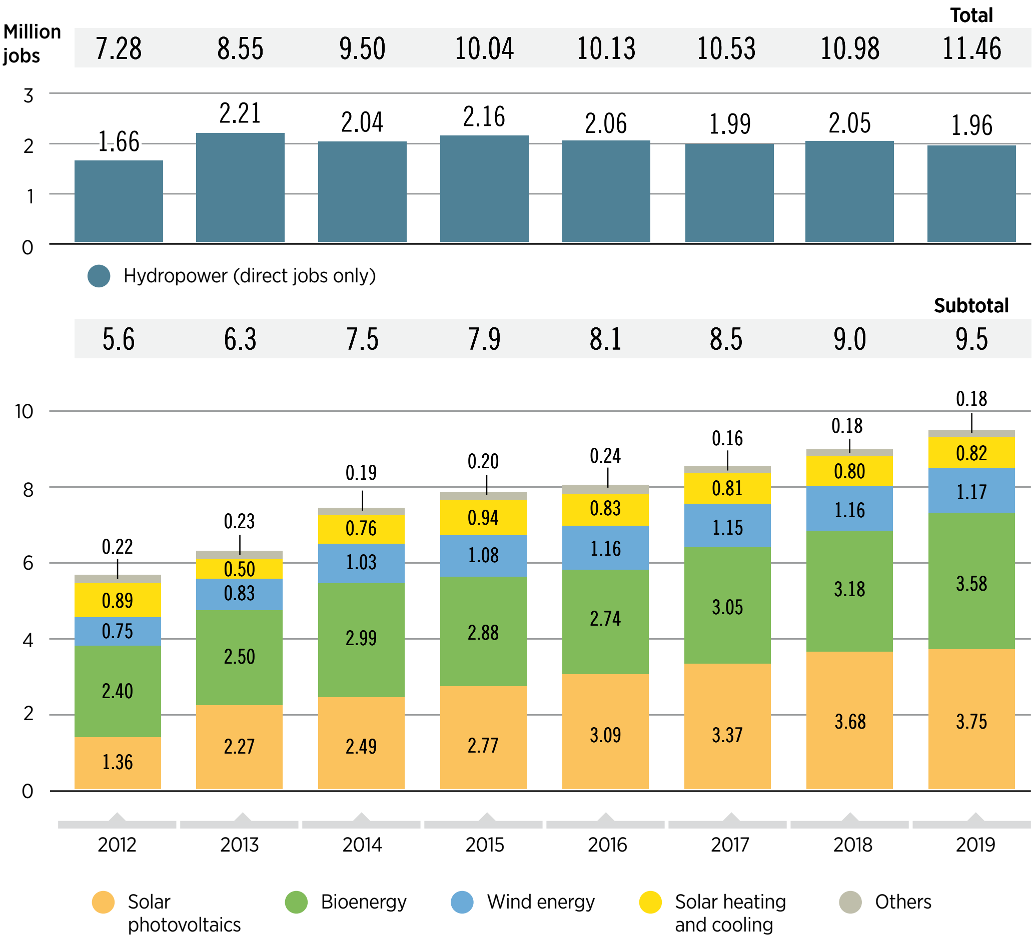


Based on IRENA's renewable energy statistics.

Innovative solutions are reshaping the energy system and opening new possibilities for a decarbonised future much faster than expected. Innovations in technology, policy and markets are being implemented worldwide (IRENA, 2019a). Significant progress has been made in electric mobility, battery storage, digital technologies and artificial intelligence, among others. These shifts are also drawing greater attention to the need for sustainable exploitation and management of rare earths and other minerals, and investment in the circular economy. New and smart grids, ranging from mini- to super grids, bolstered by facilitative policies and markets, are enhancing the power sector's ability to cope with the variability of renewables. Direct uses of renewables – including bioenergy – and green hydrogen are bringing much-needed solutions in transport, buildings and industry.

Of the 58 million energy jobs worldwide in 2019, some 20% were in the renewable sector. The change in global employment patterns reflects new trends in energy deployment. Employment grew from 7.3 million in 2012, when IRENA began monitoring jobs in renewables, to 11.5 million in 2019. During the same period, energy jobs were decreasing owing to growing automation, lack of competitiveness of some fuels and changing market dynamics. There is also growing evidence of the wider impacts of the shift toward renewables. Notably, the rise of renewables has improved the gender balance in the energy sector, with women accounting for 32% of jobs in renewables, compared with 22% in the oil and gas.

FIGURE S.2 Global renewable energy employment by technology, 2012-2019



Source: IRENA, 2020a.

The growing number of countries committing to net zero carbon strategies indicates a major shift in the global climate discourse. Similar trends are observed at all levels of government and in the private sector, including in hard to abate and oil and gas sectors. As much of the world grapples with the economic downturn, investment in the energy transition can help align short-term priorities with medium- and long-term development and climate objectives. This is a unique opportunity to instigate a lasting shift with foresighted and targeted investment in energy, most immediately in infrastructure, efficiency and renewables (IRENA, 2020b). Indeed, several countries have made significant commitments to appropriate public funds for these purposes and to support solutions such as electric mobility and clean hydrogen.

No less than 80% of the world's people live in countries that are net importers of fossil fuels. By contrast, every nation possesses some renewable potential that can be harnessed for greater energy security and independence, increasingly at least cost (IRENA, 2019b). A transformation of the global energy system aligned with the 1.5°C climate goal can become a great equaliser in a world that must become more resilient, just and inclusive. Such an energy system requires the rapid development and deployment of resilient technologies and investments in people and institutions.

Progress has been significant but uneven across geographies and communities. The longest strides have been made in a handful of countries and regions. In other areas, widespread energy poverty continues to hold back economic progress and social wellbeing. In 2020, Europe, U.S. and China accounted for the largest share of new renewable capacity, while Africa accounted for only 1% of the global total of new renewable capacity. This is even though the continent has the largest needs for expanded access to modern forms of energy and a renewable potential that far exceeds projected needs. Only USD 1 billion was invested in off-grid renewables between 2008 and 2019, despite being a major avenue for expanding access. Uneven deployment patterns are also mirrored in the concentration of jobs and industries, leaving behind large parts of the world.

Current plans fall woefully short of a 1.5°C goal. Based on existing government energy plans and targets, including the first round of Nationally Determined Contributions (NDCs) under the Paris Agreement, the policies in place will do no more than stabilise global emissions, with a slight drop as 2050 approaches. Despite clear evidence of human-caused climate change, widespread support for the Paris Agreement, and the prevalence of clean, economical, and sustainable energy options, energy-related CO_2 emissions *increased* by 1.3% annually, on average, between 2014 and 2019.

Time is of the essence, and a rapid decline in emissions must begin now to preserve a fighting chance to hold the line at 1.5°C. In alignment with the Intergovernmental Panel on Climate Change's (IPCC) report on limiting global warming to 1.5°C by 2050, coal and oil should already have peaked, with natural gas peaking in 2025. The resources and technologies needed to accelerate the energy transition are available *now*. IRENA plots the way to a steep and continuous downward trajectory towards a 45% decline in carbon dioxide (CO_2) emissions from 2010 levels by 2030, and net zero by 2050, in line with IPCC's schedule.

IRENA's *World Energy Transitions Outlook* is a unique 1.5°C-compatible pathway that also examines full socio-economic and policy implications, and provides insights on the structural changes and finance. Technologies for rapid decarbonisation are increasingly available, but thinking related to the energy transition should not be confined within the energy silo. Realising the transition's far-reaching potential requires systemic innovation that considers technologies and enabling frameworks in tandem. Renewables-based energy systems will instigate profound changes that will reverberate across economies and societies. Only by understanding these deep currents can we achieve optimal results from the transition process. This inaugural edition of the *World Energy Transitions Outlook* marshals IRENA's extensive knowledge to make this possible – by providing policy makers with insights, tools and advice to chart the path ahead.

IRENA's 1.5°C Scenario

The **Planned Energy Scenario (PES)** is the primary reference case for this study, providing a perspective on energy system developments based on governments' current energy plans and other planned targets and policies, including Nationally Determined Contributions (NDCs) under the Paris Agreement.

PES

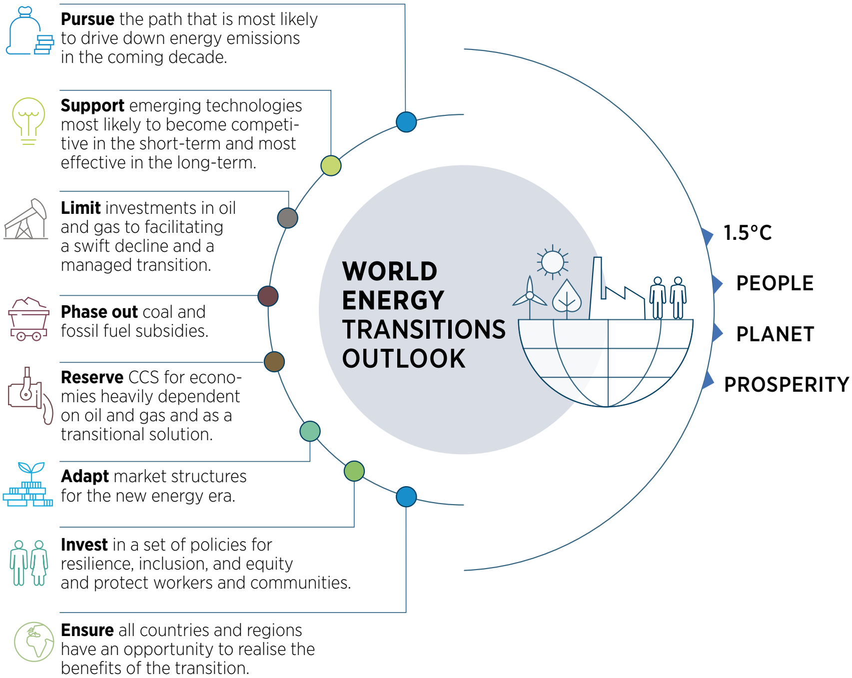
The **1.5°C Scenario (1.5-S)** describes an energy transition pathway aligned with the 1.5°C climate ambition – that is, to limit global average temperature increase by the end of the present century to 1.5°C, relative to pre-industrial levels. It prioritises readily available technology solutions, which can be scaled up at the necessary pace for the 1.5°C goal.

1.5-S

The time imperative requires careful investment and policy choices in the coming decade. The window of opportunity to achieve the 2030 emission milestone set out by the IPCC is small, and the choices made in the coming years will determine whether a 1.5°C future remains within reach. This *Outlook* is guided by the UN's Agenda for Sustainable Development and the Paris Agreement on Climate Change. Several prerequisites underpin the theory of change behind IRENA's 1.5°C Pathway:

- Pursuing the path that is most likely to drive down energy emissions in the coming decade and put the world on a 1.5°C trajectory.
- Supporting emerging technologies most likely to become competitive in the short-term and most effective in achieving emissions reductions in the long-term.
- Limiting investments in oil and gas to facilitating a swift decline and a managed transition.
- Reserving carbon capture and storage technologies for economies heavily dependent on oil and gas and as a transitional solution where no other options exist
- Phasing out coal and fossil fuel subsidies.
- Adapting market structures for the new energy era.
- Investing in a set of policies to promote resilience, inclusion, and equity and protect workers and communities affected by the energy transition.
- Ensuring all countries and regions have an opportunity to participate in and realise the benefits of the global energy transition.

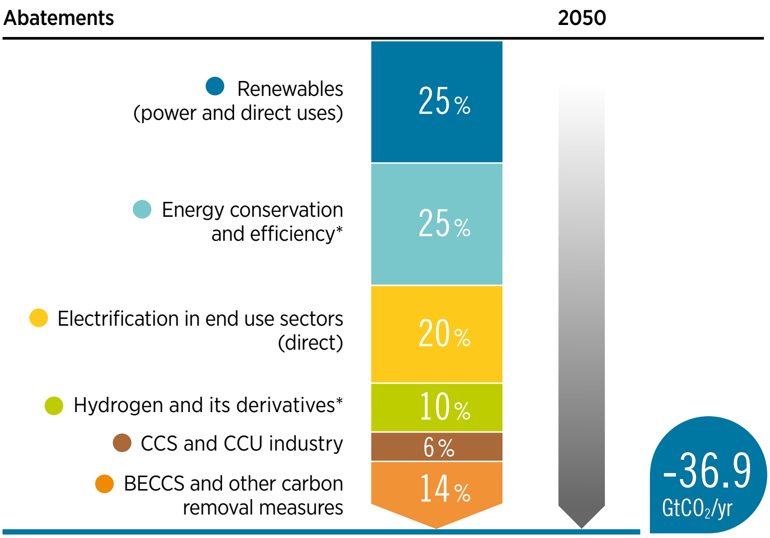
FIGURE S.3 Guiding framework of WETO theory of change



Technological avenues to climate targets

IRENA's analysis shows that over 90% of the solutions shaping a successful outcome in 2050 involve renewable energy through direct supply, electrification, energy efficiency, green hydrogen and bioenergy combined with carbon capture and storage (BECCS). The technological avenues leading to a decarbonised energy system have crystalised, dominated by solutions that can be deployed rapidly and at scale. Technologies, markets, and business models are continuously evolving, but there is no need to wait for new solutions. Considerable advancement can be achieved with existing options. But taking the energy transition technologies to the necessary levels, and at a speed compatible with a 1.5°C goal, requires targeted policies and measures.

FIGURE S.4 Carbon emissions abatements under the 1.5°C Scenario (%)



By 2050, electricity will be the main energy carrier, increasing from a 21% share of total final energy consumption in 2018 to over 50% in 2050. Sectoral boundaries are shifting, with the electrification of end-use applications in transport and heating. This increase is mostly driven by the use of renewable electricity in place of fossil fuels in end-use applications. As this shift occurs, the annual growth rate of renewable technologies will see an eightfold increase. Electrification of end-uses will also reshape several sectors, most notably transport, with electric vehicles coming to account for 80% of all road activity in 2050.

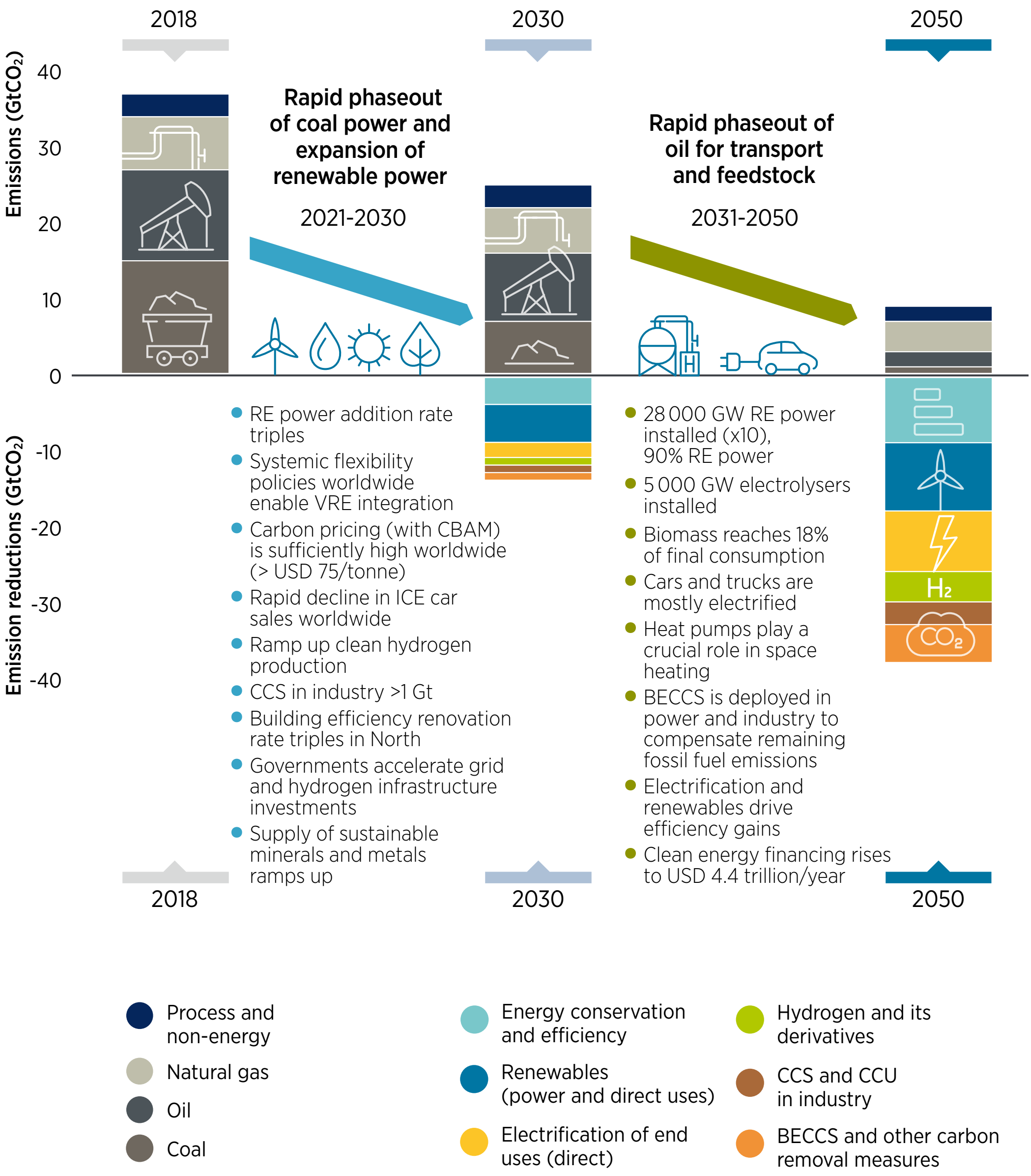
The annual energy intensity improvement rate needs to rise to 2.9%, nearly two and a half times the historical trend. With this rise, the energy intensity of the global economy will fall more than 60% by 2050. Energy efficiency technologies and measures are "ready-to-go" solutions, available for significant scale-up now. Policies and measures to increase energy conservation and efficiency will be crucial to reduce total final energy consumption from 378 exajoule (EJ) in 2018 to 348 EJ in 2050. An important contribution will also come from structural and behavioural changes, which will account for about a tenth of the improvement in efficiency.

Hydrogen and derivatives will account for 12% of final energy use by 2050. They will play an important role in hard-to-decarbonise, energy-intensive sectors like steel, chemicals, long-haul transport, shipping and aviation. Hydrogen will also help balance renewable electricity supply and demand and serve as long-term seasonal storage. Some 5 000 GW of electrolyser capacity will be needed by 2050, up from 0.3 GW today. This scale of growth accentuates the importance of low-carbon hydrogen from the outset. In 2050, two-thirds of the total hydrogen will be green – produced with renewable electricity – and one-third blue, produced by natural gas coupled with carbon capture and storage (CCS).

Bioenergy will represent 18% of total final energy consumption in 2050. Increasing sustainable production and use of biomass is needed across the energy system. In some sectors, it plays a significant role – particularly as feedstock and fuel in the chemicals sectors and as fuel in the aviation sector. In others, it helps to address gaps that other options cannot fully resolve, such as replacing natural gas with biomethane in buildings that cannot be renovated. Additionally, biomass coupled with CCS (BECCS) in the power sector and some industrial sectors will deliver the negative emissions needed to achieve the net zero goal.

In residual use of fossil fuels and some industrial processes, decarbonisation efforts may require CCS and CO_2 removal technologies and measures. In the 1.5°C Scenario, some emissions persist in 2050 from residual uses of fossil fuels and some industrial processes. Therefore, the remaining CO_2 will have to be captured and sequestered. CCS is limited mainly to process-related CO_2 emissions in cement, iron and steel, and blue hydrogen production. CO_2 removal includes nature-based measures such as reforestation and BECCS, direct carbon capture and storage, and other approaches that are still experimental.

FIGURE S.5 Evolution of emissions with phaseouts of coal and oil, 2021-2050



Note: RE = renewable energy; VRE = variable renewable energy; CBAM = carbon border adjustment mechanism; ICE = internal combustion engine; GW = gigawatt; Gt = gigatonne; CCS = carbon capture and storage; BECCS = bioenergy combined with carbon capture and storage; CCU = carbon capture and utilisation.

By 2030, renewable power should reach 10 700 GW globally, almost quadrupling the current capacity. Rapid scale-up deployment in the coming decade is necessary to set the stage for decarbonisation of the power system and electrification of end-use by 2050. This level of deployment is also a key recommendation of the Energy Transitions Theme Report, developed by IRENA, UNEP, and UN ESCAP for the United Nations High-Level Energy Dialogue. The abundance of cost-effective renewable potentials worldwide makes them a scalable option. For many countries, this translates a technical and economic challenge into a set of investment, regulatory and societal opportunities.

Infrastructure upgrade, modernisation and expansion is a high priority in the coming decade. Updating ailing infrastructure or investing in expansion is an integral part of the energy transition and an enabler of modern technologies. This will be particularly important in the coming decade as the share of renewables grows, requiring system flexibility and modern grids. Infrastructure developments must be aligned with long-term plans and reflective of broader strategies, including regional market integration.

The necessary deployment levels will be reached by 2030 only with policies to support these technological avenues. Deployment policies support market creation, thus facilitating scale-up, reducing technology costs and increasing investment levels aligned with energy transition needs. Given the large amounts of public finance being injected into economies as part of the recovery measures, such policies will shape the direction of the energy transition and set the stage for the significant increase in the private sector investment required until 2050.

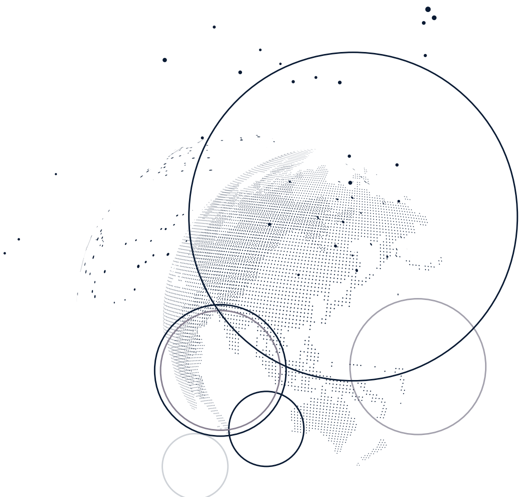


TABLE S.1 Overview of policies to support energy transition solutions

TECHNOLOGICAL AVENUE	OBJECTIVE	RECOMMENDATIONS
Renewables (power and direct uses)	Deploy renewable energy in end uses	These policies include regulatory measures that create a market, as well as fiscal and financial incentives to make them more affordable and increase their cost competitiveness compared to fossil-fuel-based solutions.
	Deploy renewable energy in the power sector	The choice of instrument and its design should consider the nature of the solution (*e.g.*, utility scale, distributed, off-grid), the sector's level of development, the power system's organisational structure and broader policy objectives.
Energy conservation and efficiency	Increase energy conservation and efficiency in heating and cooling	Energy efficiency policies such as strict building codes, support for building retrofits and appliance standards are critical for the energy transition in buildings and industrial processes.
	Increase energy conservation in transport	Decarbonising the transport sector, among other measures, requires a shift from energy-intensive modes to low-carbon modes.
Electrification of end uses	Electrify heating and cooling	Targets for renewable power should consider the rising demand from the electrification of end uses, in line with long-term decarbonisation objectives. Moreover, policies and power system design are needed to support electrification in achieving its potential for providing system flexibility.
	Electrify transport	
Green hydrogen	Support the development of green hydrogen	An enabling policy framework should consider four key pillars: a national green hydrogen strategy, priority setting, guarantees of origin and enabling policies.
Sustainable bioenergy	Ensure the sustainable use of bioenergy	Renewable energy is not exempt from sustainability concerns. Some of these concerns include greenhouse gas emissions related to land-use change, and impacts on air and water quality and biodiversity.

Financing the energy transition

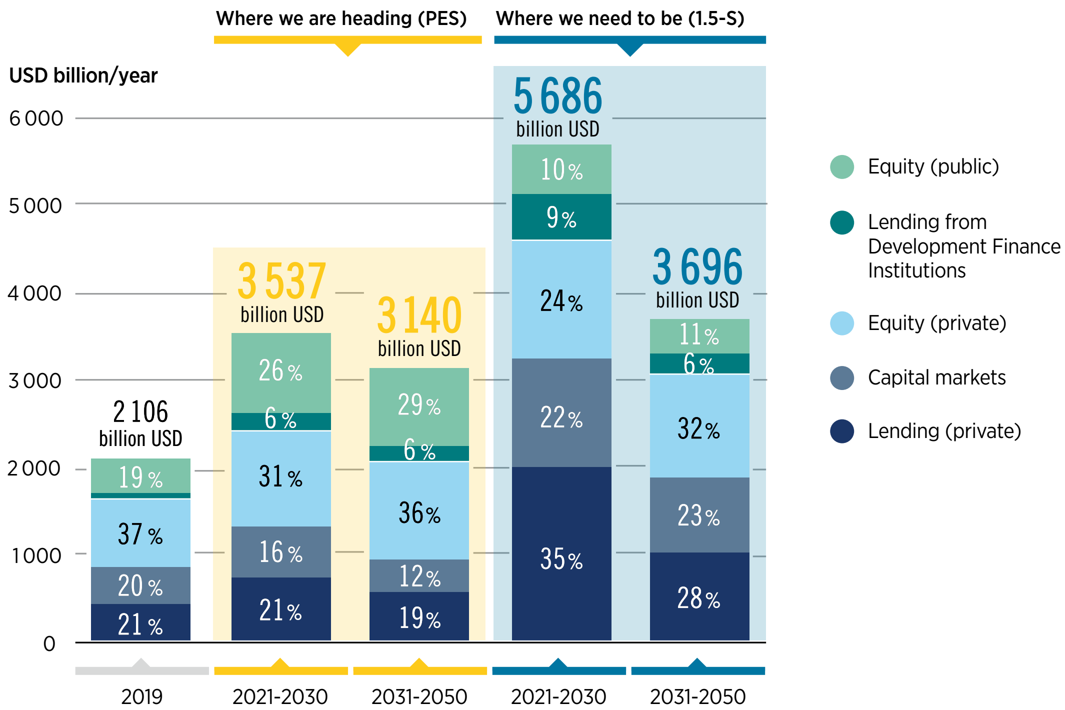
USD 131 trillion will need to flow into an energy system over the period to 2050 that prioritises technology avenues compatible with a 1.5°C Pathway. While the annual funding requirement averaging at USD 4.4 trillion is large, it represents 20% of the Gross Fixed Capital Formation in 2019, equivalent to about 5% of global Gross Domestic Product (GDP). Between now and 2050, over 80% of the USD 131 trillion total must be invested in energy-transition technologies, including efficiency, renewables, end-use electrification, power grids, flexibility, hydrogen, and innovations designed to help emerging and niche solutions become economically viable.

Current government strategies already envisage significant investment in energy amounting to USD 98 trillion by 2050. Collectively referred to in this Outlook as the Planned Energy Scenario (PES), they imply a near doubling of annual energy investment, which in 2019 amounted to USD 2.1 trillion. Substantial funds will flow towards modernisation of ailing infrastructure and meeting growing energy demand. But the breakdown of financing for technology under the 1.5°C Scenario differs greatly from current plans: USD 24 trillion of planned investments will have to be redirected from fossil fuels to energy transition technologies between now and 2050.

Funding structures in the 1.5°C Scenario are markedly different in terms of capital sources (public and private) and types of capital (equity and debt). In 2019, USD 1.6 trillion in energy assets were financed by private sources, accounting for 80% of total energy sector investment. That share would grow dramatically under the 1.5°C Scenario. The share of debt capital has to increase from 44% in 2019 to 57% in 2050, almost 20% more than under the PES (see Figure S.6). Energy transition technologies should find it increasingly easy to obtain affordable long-term debt financing, while "brown" assets will progressively be avoided by private financiers and therefore forced to rely on equity financing from retained earnings and new equity issues. Capital-intensive, more decentralised projects will influence investors' risk perception, which in turn may need targeted policy and capital market interventions.

Public funding will need to grow almost two-fold to catalyse private finance and ensure just and inclusive unfolding of the energy transition. Public financing plays a crucial role in facilitating the energy transition, as markets alone are not likely to move rapidly enough. In 2019, the public sector provided some USD 450 billion in the form of public equity and lending by development finance institutions. In the 1.5°C Scenario, these investments will grow to some USD 780 billion. Public debt financing will be an important facilitator for other lenders, especially in developing markets with high real or perceived risks. In some instances, this may include grants to reduce the cost of financing. Public funds are also needed to create an enabling environment for the transition and ensure that it occurs fast enough and with optimal socio-economic outcomes.

FIGURE S.6 Total average yearly investment by source and type of financing: 2019, PES and 1.5°C Scenario (2021-2030 and 2031-2050)



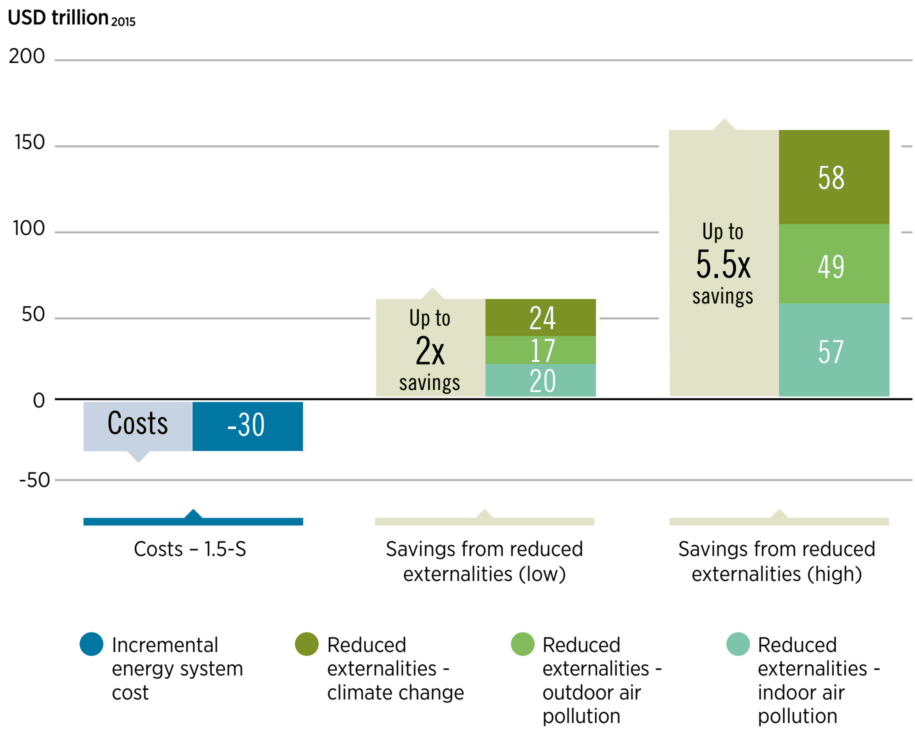
Sources: For 2019 investment: source and type of financing BNEF (2021a), IEA (2020a), IRENA and CPI (2020); for PES and 1.5°C Scenario: IRENA and BCG analysis.

Measures to eliminate market distortions that favour fossil fuels, coupled with incentives for energy transition solutions, will facilitate the necessary changes in funding structures. This will involve phasing out fossil fuel subsidies and changing fiscal systems to reflect the negative environmental, health and social costs of the fossil fuel-based energy system. Monetary and fiscal policies, including carbon pricing policies, will enhance the competitiveness of transition-related solutions. Such interventions should be accompanied by a careful assessment of the social and equity dimensions to ensure that the situation of low-income populations is not worsened but improved.

Socio-economic footprint of the energy transition

Investment in the 1.5°C Scenario will yield a cumulative payback of at least USD 61 trillion by 2050. The overall balance from the energy transition is positive, with benefits greatly exceeding costs. The costs for reducing emissions vary by technology and sector, but the incremental costs are significantly lower than the savings achieved by cutting external costs. IRENA estimates that, under the 1.5°C Scenario, every USD 1 spent on the energy transition should yield benefits from reduced externalities from human health and the environment valued at between USD 2 and USD 5.5. In cumulative terms, the additional USD 30 trillion cost implied by the 1.5°C Scenario over the period to 2050 will result in a payback of between USD 61 and USD 164 trillion.

FIGURE S.7 **Cumulative difference between costs and savings of 1.5°C Scenario compared to the PES, 2021-2050**



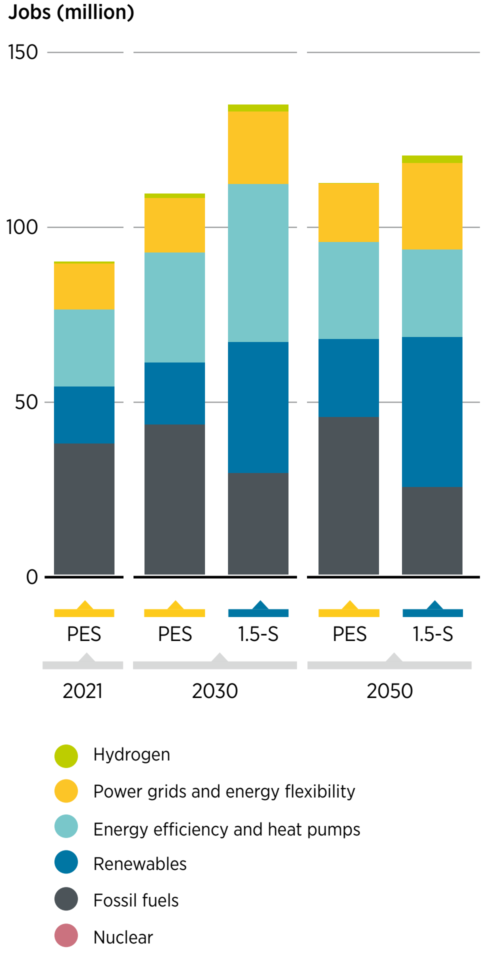
The energy transition goes well beyond technology and brings deep structural changes that will greatly affect economies and societies. IRENA continues to capture an increasingly comprehensive picture of the socio-economic impacts of the energy transition. Results presented in this *Outlook* demonstrate that steps towards a decarbonised energy future will positively affect economic activity, jobs and welfare, provided a holistic policy framework is in place. Within the analysis, countries' existing policies are complemented with climate policies to reach energy transition targets while addressing distributional challenges for just and inclusive outcomes.

The 1.5°C Pathway provides a boost in GDP that is 2.4% greater (on average) than that of the PES over the next decade, aligned with the needs of a post-COVID recovery. Over the transition period to 2050, the average improvement of GDP is estimated at 1.2% over the PES. Additional GDP growth will be spurred by investment across the many dimensions of the energy transition, leading to multiple adjustments between interdependent economic sectors. The reduced demand for fossil fuels leads to lower revenues for mining and fuel refining industries, as well as for governments (because of lower fossil fuel royalties), thus resulting in negative impacts on GDP in some countries. This reality highlights the need for a holistic policy framework that addresses structural changes caused by reduced fossil fuel dependency.

Throughout the transition period, economy-wide employment is 0.9% higher on average under the 1.5°C Scenario than under the PES. One of the main positive impacts on employment comes from investment in energy transition solutions, including renewables, grid enhancement and energy efficiency. Shifting investment from fossil fuels (extraction and power generation) and other sectors towards the energy transition decreases labour demand in fossil fuel and non-energy sectors and along their value chains.

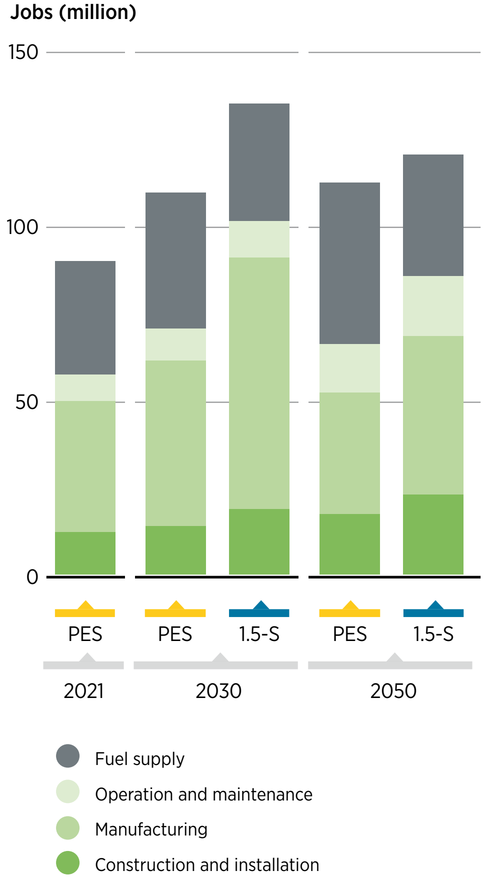
A transformed energy sector will have 122 million jobs in 2050. Qualifications, skills and occupations under the ambitious 1.5°C Scenario are increasingly concentrated in manufacturing, followed by fuel supply. Training for such occupations is relatively easy and offers opportunities for workers from the fossil-fuel industry. The educational requirements for the labour force evolve during the transition, with a continuous increase of the share and number of workers with primary education and a peak of workers with tertiary education by 2030.

FIGURE S.8 Energy sector jobs by technology under the PES and 1.5°C Scenario (million), global results



Based on IRENA's analysis.

FIGURE S.9 Energy sector jobs, by segment of value chain, in the 1.5°C Scenario and PES (excluding vehicles)



Based on IRENA's analysis.

Renewable energy jobs will increase to 43 million in 2050. In the PES, renewable energy jobs increase 9% from 2021 values to reach 18 million jobs by 2030 and 23 million by 2050. By contrast, the 1.5°C Scenario leads to a much larger gain by 2030, with renewables jobs more than tripling to 38 million over the coming decade. Solar photovoltaic (PV) accounts for the largest share, followed by bioenergy, wind and hydropower. Construction, installation and manufacturing boost renewable jobs during the following decade, with operation and maintenance gaining relative weight as the transition advances under the 1.5°C Scenario.

FIGURE S.10 Jobs in renewable energy, by technology, in the 1.5°C Scenario and PES (million)

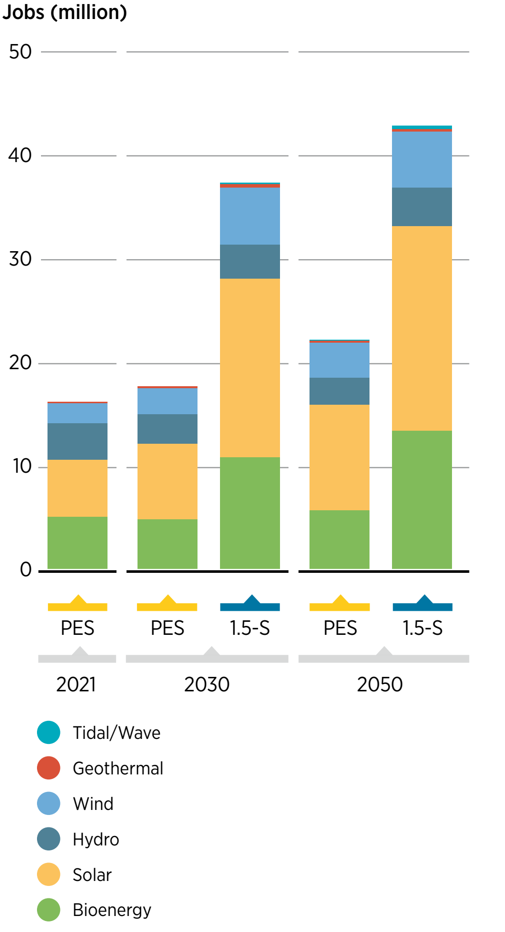
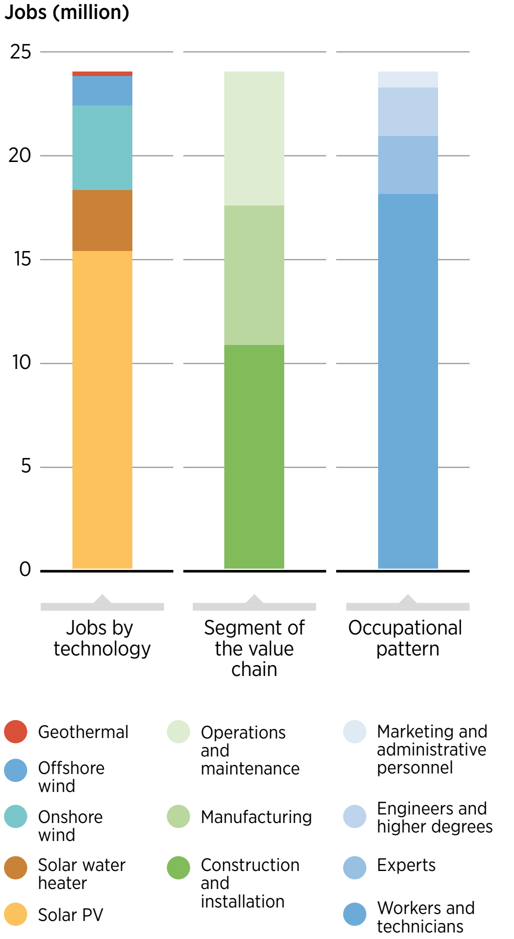


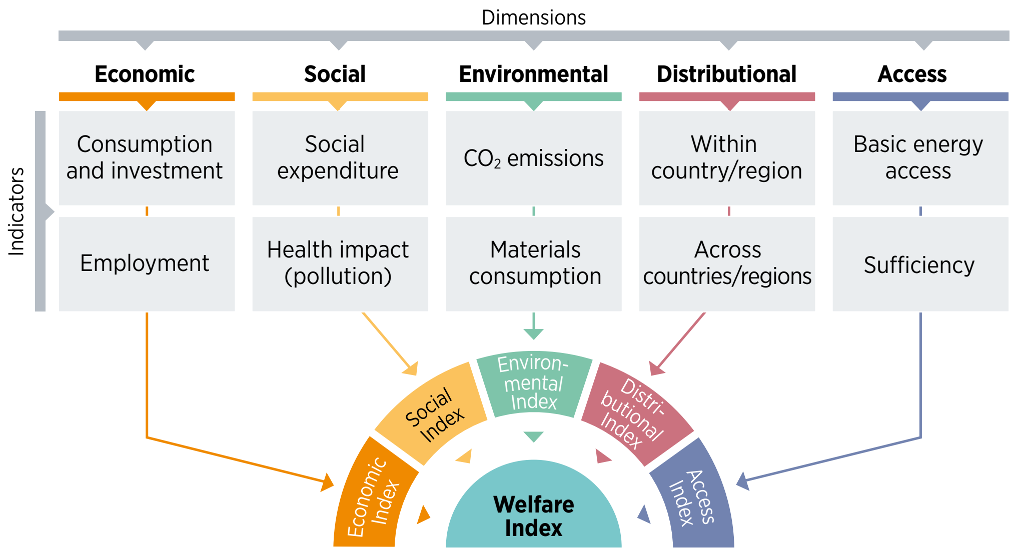
FIGURE S.11 Structure of jobs in the 1.5°C Scenario by 2050 for a subset of renewable technologies by technology, segment of value chain and occupational requirements



Based on IRENA analysis.

IRENA's Energy Transition Welfare Index captures economic, social, environmental, distributional and energy access dimensions. For the first time, the Index reports distributional and energy access dimensions that are often overlooked in other analyses. Measuring the impact of the transition across these dimensions provides a quantitative basis for roadmaps designed to reap the transition's full socio-economic and environmental benefits.

FIGURE S.12 Structure of IRENA's Energy Transition Welfare Index



The 1.5°C Scenario performs better than the PES along all welfare dimensions, yielding an 11% improvement over the PES by 2050.

- The ***economic dimension*** is similar for both scenarios reflecting the energy sector's relatively small share in the overall global economy and labour force.
- The ***environmental dimension*** sees a 30% improvement over PES with significantly lower emissions under the 1.5°C Scenario, although increased materials consumption poses sustainability challenges.
- The ***social dimension*** improves 23% under the 1.5°C Scenario largely due to improved health outcomes from lower outdoor and indoor air pollution. Social expenditures contribute a much smaller role.
- The ***distributional dimension*** improves 37% over PES; however, the index remains low in an absolute sense, indicating potential equity barriers. In fact, both social and distributional dimensions bring down the overall Energy Transition Welfare Index – and these realities deserve more policy attention.
- The ***energy access dimension*** grows 7% under the 1.5°C Scenario compared to PES as universal energy access and sufficiently levels are reached.

Socio-economic impacts vary at the regional and country level. Global aggregates mask important differences in how the energy transition affects regions and countries and how benefits are distributed. What is clear is that the energy transition roadmaps and their resulting socio-economic implications are closely linked with the policy framework, with those links becoming stronger as ambitions align with the 1.5°C Pathway. Governments' involvement in the transition should be accompanied by international co-operation to ensure that the benefits and burdens of the transition are equitably shared.

TABLE S.2 Overview of structural change and just transition policies

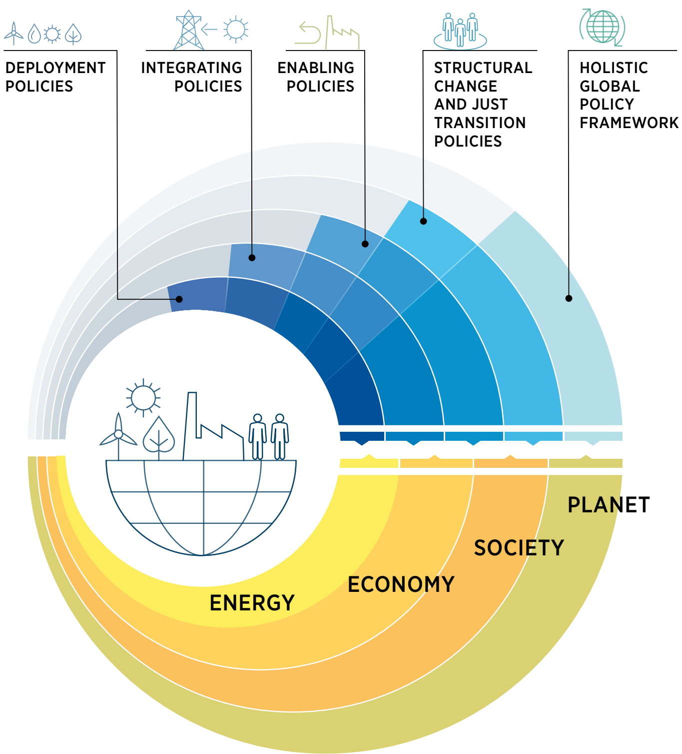
OBJECTIVE	RECOMMENDATIONS
Address potential misalignments in labour markets	Ensuring a just and fair transition will require measures to overcome temporal, geographic and skills-related imbalances.
Develop local value chains	Enhancing and leveraging domestic capabilities requires carefully crafted incentives and rules, business incubation initiatives, supplier-development programmes, support for small and medium enterprises and promotion of key industrial clusters.
Provide education and build capacity	Early exposure to renewable-energy-related topics and careers is vital for sparking young people's interests in pursuing a career in the sector, and also to increase social acceptance by a knowledgeable citizenry.
Support a circular economy	Policies and measures are needed to ensure the sustainability of energy transition-related solutions and their smooth integration in existing ecosystems in terms of sustainability, circular economy principles and reduced environmental impacts.
Support community and citizen engagement	Community energy can play an important role in accelerating renewables deployment while generating local socio-economic benefits and increasing public support for local energy transitions.

A comprehensive policy framework for the energy transition

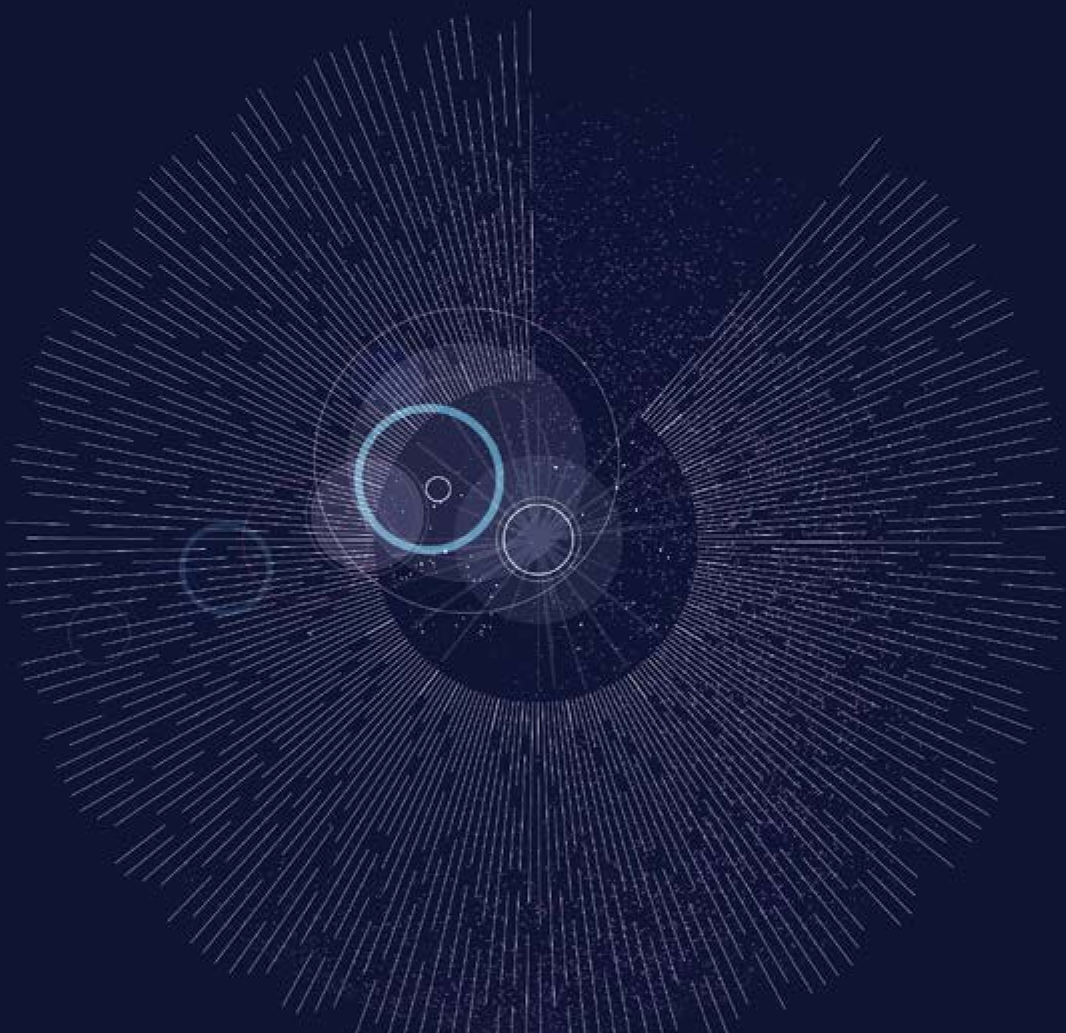
Policy measures and investments in energy transitions can drive a wider structural shift towards resilient economies and societies. The energy sector must be viewed as an integral part of the broader economy to fully understand the impact of the transition and ensure that it is timely and just. Regions and countries have varied starting points, socio-economic priorities and resources, all of which shape the scope and pace of their energy transition. Energy transitions trigger structural changes that bring benefits as well as challenges, with those challenges appearing in the form of misalignments in finance, labour markets, power systems and the energy sector itself. These misalignments, if not well managed, risk inequitable outcomes and a slowdown in the energy transition. Just and integrated policies – implemented by strong institutions – are imperative to realise the full potential of the energy transition.

International co-operation is an essential piece of the global energy transition. A holistic global policy framework is needed to bring countries together to commit to a just transition that leaves no one behind and strengthens the international flow of finance, capacity and technologies. Climate policies represent a crucial element in such a framework. Other measures should include fiscal policies (such as adequate carbon pricing covering emissions across sectors) and public funding to implement policies to foster deployment, create enabling conditions and ensure a just and stable transition. Elements of the latter imperative include industrial development, education and training, and social protection. The necessary financial resources will not always be available domestically. International co-operation will be needed to provide such support, particularly to the least-developed countries and small island developing states.

FIGURE S.13 Enabling policy framework for a just and inclusive energy transition



01 LEVERAGING THE COMPETITIVENESS OF RENEWABLES TO HASTEN THE ENERGY TRANSITION AND MINIMISE CLIMATE CHANGE



The energy sector has experienced unprecedented dynamism in recent years largely due to the advent of renewables.

Traditionally slow to change, the energy sector has experienced unprecedented dynamism in recent years, quite unlike any other time in history. This is in large part due to the advent of renewables. While the share of renewables in the overall energy mix remains limited at a global scale, technologies used to harness the sun and wind are reshaping the energy systems of the past, with wide-ranging and outsized implications. Meanwhile, policy priorities such as climate change, energy security, energy access and air pollution have placed a renewables-based energy transition at the forefront of the national, regional and global discourse.

In the turmoil caused by the COVID-19 pandemic, renewables showed remarkable resilience. This further cemented their role in decarbonising economies worldwide and, through their potential to create jobs, in supporting economic recovery. Combined, these developments are shifting renewables from niche to mainstream, as even the most traditional players come to embrace their immense promise. Importantly, renewables-based solutions are necessary to policy makers in their quest to limit the global temperature rise to 1.5°C by 2050, with net zero emissions. Such solutions increasing adoption sends an important message regarding the urgency of combating climate change (Lederman and Chow, 2021). The strong financial performance of green investments has attracted the interest of the financial community in supporting the climate cause and is likely to encourage a new trend in investments.

This chapter presents a brief overview of the most relevant recent developments in the energy transition. It outlines key trends at a moment in time when over 100 nations are at different stages of operationalising their net zero carbon targets for 2050. Even as each country considers how to accomplish this in light of its own circumstances, endowments, abilities and needs, all countries are on the cusp of transforming their energy sectors. The chapter thus introduces a pathway towards maintaining the 1.5°C limit, here called the 1.5°C Scenario. As it clarifies key assumptions underlying the scenario, and outlines its parameters, the chapter sets the stage for a more detailed discussion of climate scenarios in the ensuing chapters.

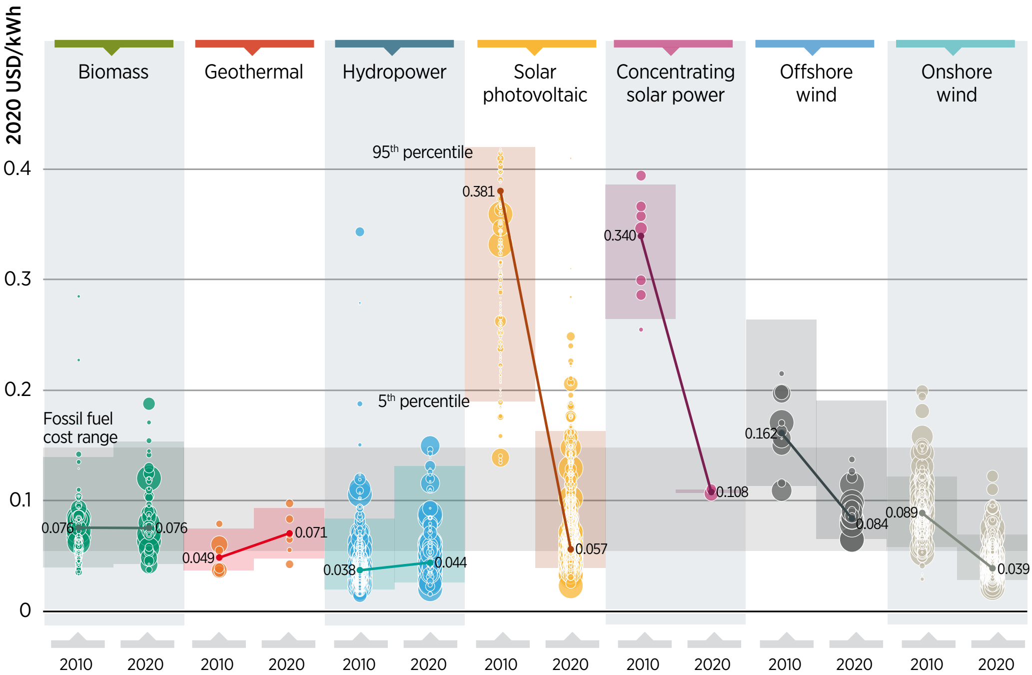
1.1 ENERGY TRANSITION TRENDS

Renewables are increasingly the lowest-cost sources of electricity in many markets. It has been a remarkable decade of change for renewable electricity generation, and solar photovoltaic (PV) and wind power technologies in particular. Among newly commissioned projects, the global weighted average levelised cost of energy (LCOE) of utility-scale solar PV fell by 85% between 2010 and 2020, from USD 0.381/kilowatt hour (kWh) to USD 0.057/kWh (Figure 1.1). This is a precipitous decline. At one time more than double the cost of the most expensive fossil-fuel-fired power generation option, utility-scale solar PV can now compete with the cheapest new fossil-fuel-fired capacity.[1] Between 2010 and 2020, the global weighted-average cost of electricity from onshore wind projects fell by 56%, from USD 0.089/kWh to USD 0.039/kWh. Over the same period, the global weighted average cost of electricity from concentrating solar power fell from USD 0.340/kWh to USD 0.108/kWh. This 68% decline in the cost of electricity from this technology – which now falls in the middle of the range of new fossil-fuel capacity – remains a remarkable achievement. For offshore wind, the global weighted average LCOE of newly commissioned projects declined from USD 0.162/kWh in 2010 to USD 0.084/kWh in 2020, a reduction of 42% in ten years (IRENA, 2021b). Falling technology costs continue to affect auctions, where new record-low prices continued to emerge even amid the global pandemic. For example, in 2020, Abu Dhabi saw a USc 1.35/kWh bid for solar PV (Ombello, 2020), followed by an even lower bid in a Portuguese auction in July (Bellini, 2020).

1 The cost of fossil-fuel-fired power generation varies by country and fuel in an estimated range between USD 0.055/kWh and USD 0.148/kWh. The lower bound represents new, coal-fired plants in China.

The costs of renewable energy have continued to decline. Solar PV and wind are increasingly the cheapest sources of electricity in many markets.

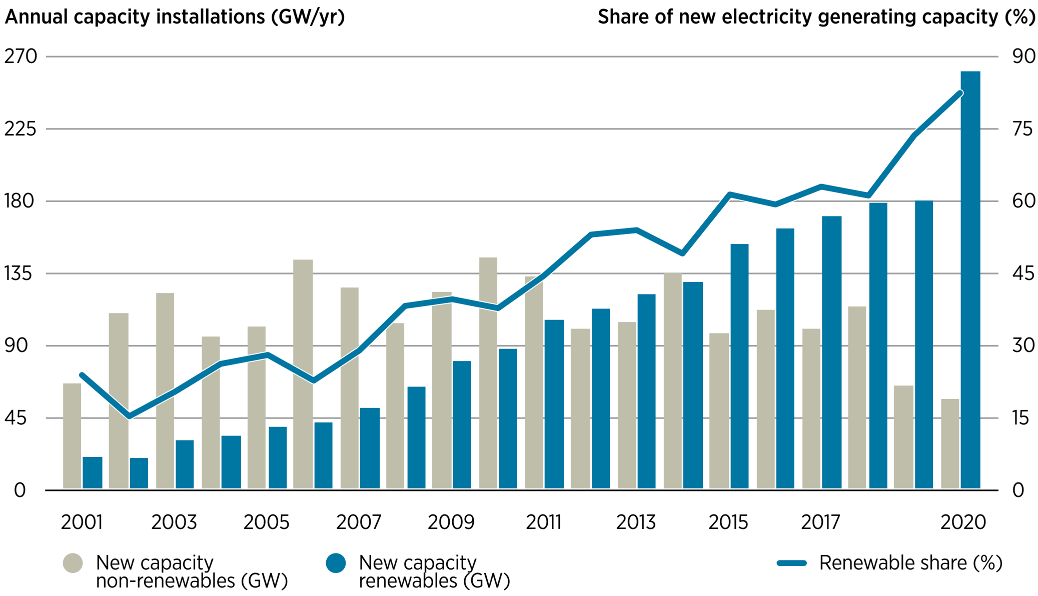
FIGURE 1.1 Global LCOE of newly commissioned utility-scale renewable power generation technologies, 2010 and 2020



Source: (IRENA, 2021b)

More renewable power capacity was added to the grid annually than all fossil fuels and nuclear combined in the seven years between 2013 and 2020. The share of renewable energy in electricity generation also increased steadily. Renewable power technologies now dominate the global market for new electricity generation capacity. Despite the pandemic's detrimental effects on most global supply chains, more than 260 gigawatts (GW) of renewable generation capacity – a record level – was added globally in 2020 (Figure 1.2). This is more than four times the capacity added from other sources and nearly 50% more than the 2019 addition (IRENA, 2021a). The upward trend in these shares reflects not only the rapid and increasing growth in the use of renewables but also a a decline in the growth of non-renewable capacity, following net decommissioning across many years in some regions. The impact of the pandemic on wind and solar PV has been much smaller than anticipated and both sources have continued dominating new capacity installations, showing the resilience and momentum of the renewables industry. A total of 111 GW of wind power were installed in 2020, compared to 60 GW in 2019; solar PV additions reached 127 GW in 2020 (IRENA, 2021a). As renewable electricity generation capacity increases so does the share of renewables in electricity generation, which increased from 20% to nearly 28% in the years 2010-2020 (IEA, 2020b). This capacity growth is concentrated in a limited number of countries and regions.

FIGURE 1.2 Share of new electricity capacity, 2001-2020



Based on IRENA's renewable energy statistics.

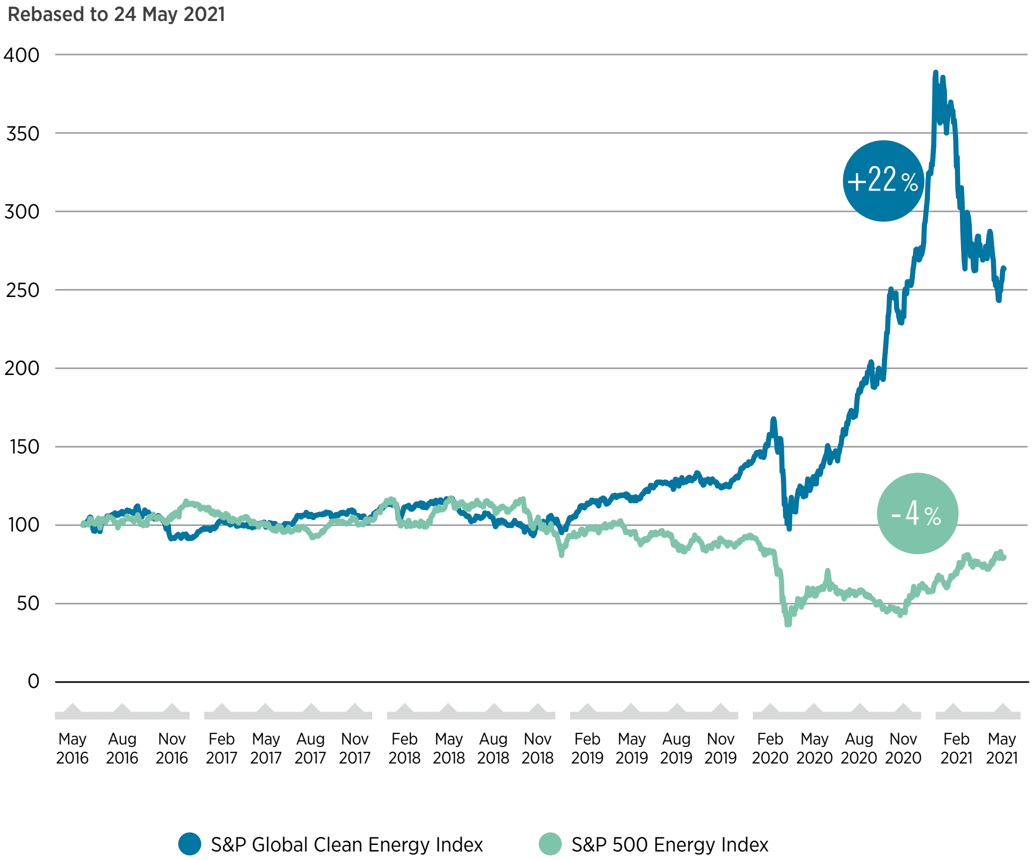
Note: GW = gigawatt.

A record level of more than 260 GW of renewable generation capacity was added globally in 2020. This is more than four times the capacity added from other sources and nearly 50% more than the 2019 addition.

Growing shares of variable renewable energy (VRE), such as solar and wind in power systems, complicate the balancing of supply and demand, raising system requirements. **To effectively manage large VRE shares, a wide range of innovations are being implemented around the world** (IRENA, 2019a). Significant progress has been made in battery storage, digital technologies (*i.e.*, Internet of Things, artificial intelligence, big data), as well as new and smart grids (mini-grids and super grids), contributing to better management of a power sector that is seeing the increasing integration of variable renewables. On the business and regulatory side, new and innovative models (*i.e.*, aggregators, pay-as-you-go and community ownership), as well as market regulations are empowering consumers while also helping manage the greater shares of VRE generation. Aggregators' business models are picking up, as well. The global market for virtual power plants is projected to grow from less than USD 1 billion in 2019 to around USD 2.85 billion by 2027, with a compound annual growth rate of 27.2% (FBI, 2020).

Capital is increasingly moving to take advantage of the most attractive investment opportunities at this time of transition. Anticipating that demand for fossil fuels will soon peak as new energy technologies continue their rapid growth, financial markets are allocating capital in new ways. After the shock induced by the COVID-19 pandemic in March 2020, investors became enthusiastic about the opportunity presented by renewables, which resulted in a spike in the value of clean energy stocks (Figure 1.3). Although the S&P Global Clean Energy Index followed a downward trend from the beginning of 2021, in the five years from May 2016 to May 2021, the index was up by 22%, while the fossil-fuel-heavy S&P 500 Energy Index was down by 4%, suggesting an emerging trend in financial markets towards cleaner energy assets.

FIGURE 1.3 **New energy vs. old energy: S&P Global Clean Energy and Energy Indices, 24 May 2016 to 24 May 2021**



Source: S&P Dow Jones Indices LLC, 2021.

Investors and financial markets are anticipating the energy transition and already allocating capital away from fossil fuels and towards energy transition technologies, such as renewables.

In 2020, investment in the global energy transition hit a record high of USD 524 billion, having grown steadily for over 15 years (Figure 1.4) (BNEF, 2021a).[2] Renewable energy technologies dominated these investment flows, though their share decreased over time (from almost 90% in 2005-2009 to 70% in 2016-2020) as other energy transition technologies attracted increasing volumes of capital. In addition, investments in energy efficiency averaged just above USD 250 billion during 2014-2019 (IEA, 2020a).

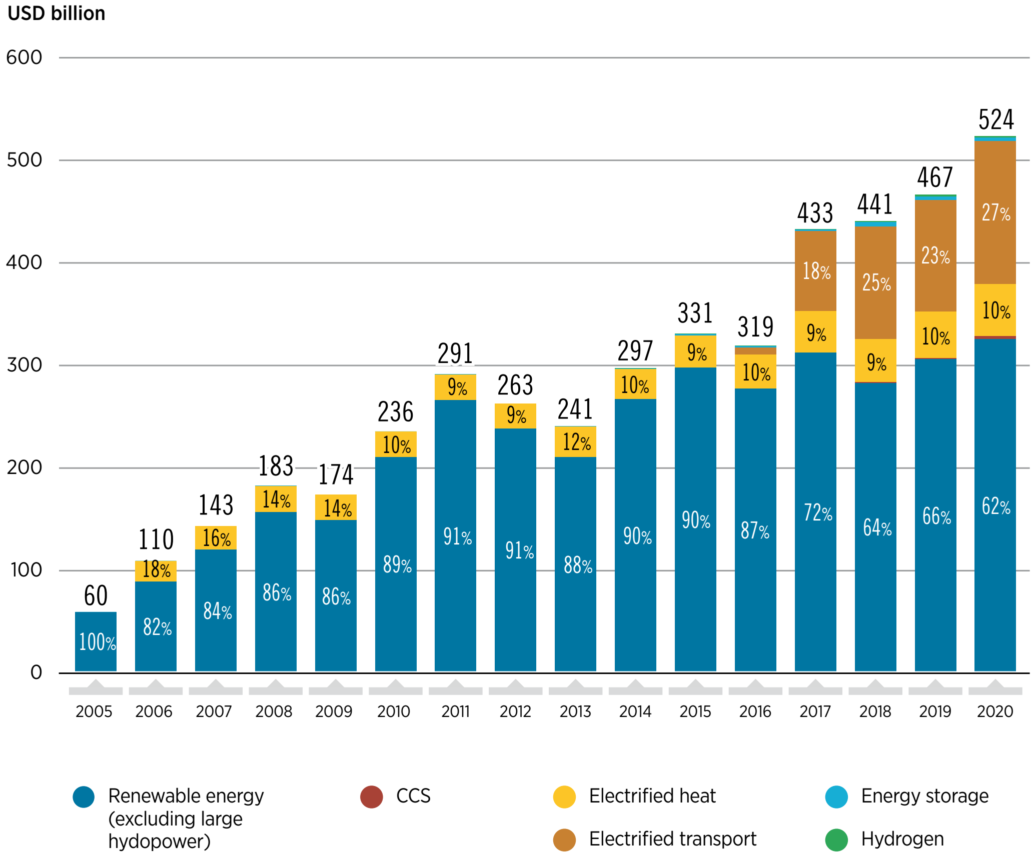
Investments in electrified transport are also on the rise, as policies supporting the electrification of transport gain importance. In 2017, at least 60 countries and 40 jurisdictions at the sub-national level had set objectives for the deployment of electric vehicles (REN21, 2018). By the end of 2019, at least 13 jurisdictions had introduced financial incentives to support their deployment (REN21, 2020). Policies to support electric vehicles – including public procurement, public support for charging infrastructure, congestion charging, free parking and preferred access – have supported a surge in uptake. All of the top markets for electric vehicles to date (*e.g.*, China, Norway and the United States) have introduced such policies.

Investments in electric heat have also increased in the past couple of years as more countries adopted financial incentives for their installation such as grants, rebates, tax incentives and loan programmes. In 2019, France, Germany and Lithuania implemented instruments to support the phase-out of inefficient fossil fuel boilers and the adoption of heat pumps.

2 This figure measures investments in renewables (excluding large hydropower), electrified heat, electrified transport, energy storage, hydrogen and carbon capture and storage (CCS). Including investments in energy efficiency, the total rises to almost USD 800 billion.

Despite the COVID-19 pandemic, investment in energy transition technologies reached an all-time high of USD 524 billion in 2020 – up to almost USD 800 billion if energy efficiency measures are considered.

FIGURE 1.4 Global investment in energy transition technologies, 2005-2020



Source: BNEF 2021a.

Note: BNEF data exclude investments in large hydropower (*i.e.*, greater than 50 MW), estimated at USD 28 billion on average per year between 2015 and 2019. CCS = carbon capture and storage.

1.2 THE EVOLVING POLICY LANDSCAPE

The number of countries with renewable energy policies has grown significantly. In 2019, 143 countries had policies for renewables in the power sector compared with 117 in 2014 (REN21, 2020). As market conditions evolve alongside the maturity and competitiveness of technologies, the preferred policy instruments have adapted over time. For instance, competitively set pricing mechanisms for renewable power are replacing administratively determined tariffs. The number of countries adopting renewable energy auction schemes have increased from 16 in 2010 to 109 in 2020. During this period, the weighted global average price of contracted solar energy fell from USD 250/megawatt hours (MWh) to USD 56/MWh and that of onshore wind decreased from USD 75/MWh to USD 48/MWh (IRENA, 2019c). As the share of renewable electricity has grown, integration, flexibility and power market design have also come to the fore in policy design and implementation.

Policies to promote the use of renewable energy in end-use sectors have received less attention. In 2019, 61 countries had introduced heating and cooling policies (IRENA, 2020c). Financial policies, such as investment subsidies, grants, rebates and tax credits are more common than regulatory policies such as renewable heating mandates. Given the context-specific and decentralised nature of heating and cooling needs, local governments also play a key role. At least 110 cities and municipalities are targeting 100% renewable heating and cooling. In the transport sector, 70 countries have introduced renewable energy policies largely focused on road transport and the use of liquid and gaseous biofuels.

It is abundantly clear that accelerating the pace and depth of the energy transition will require a continuing focus on the power sector, along with much greater policy efforts in electrification, as well as the heating and cooling and transport sectors.

Also, countries are increasingly adopting policies dedicated to off-grid renewables. Tailored regulations for mini-grids have been adopted in countries such as Nigeria, Tanzania, Uganda, Mali, Senegal, India and Indonesia, driving investments in these technologies. The regulations usually address aspects related to licensing and legal provisions, tariff setting, the implications of main-grid arrival and public financing support.

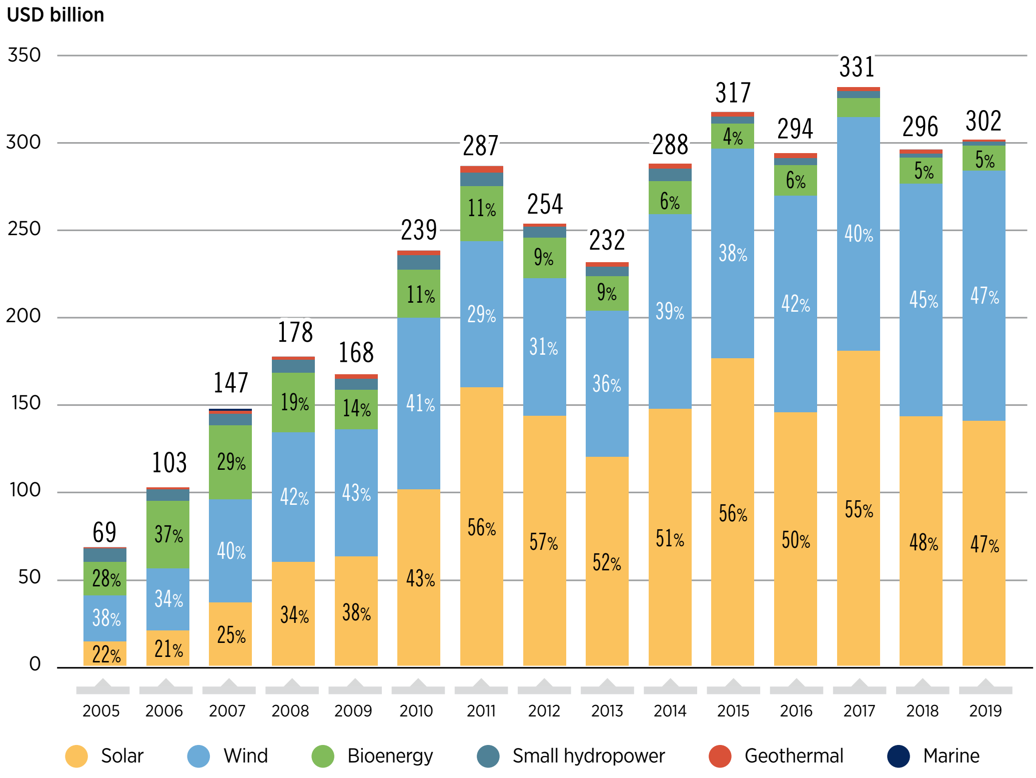
1.3 RENEWABLE ENERGY INVESTMENTS

With falling costs, renewable energy investments grew steadily over the past 15 years, from USD 70 billion in 2005 to just over USD 300 billion in 2019. In 2020, despite the dramatic impacts of the COVID-19 pandemic, investments in renewables reached over USD 320 billion (BNEF, 2021a). Solar and wind technologies have consolidated their dominance over time, having attracted combined shares of total investments above 90% since 2014 (Frankfurt School-UNEP Centre and BNEF, 2020; BNEF, 2021a; IRENA and CPI, 2020) (Figure 1.5).

Despite their steady growth overall, renewable energy investments remained concentrated in a handful of regions and countries. The Asia-Oceania region, led by China, regularly attracts the largest share of renewable energy investments (on average, 55% during 2005-2019). Europe and the United States follow, with average shares of 20% and 16%, respectively, during 2005-2019. Regions dominated by developing and emerging economies remained consistently under-represented, attracting only about 15% of global investments in renewables (Frankfurt School-UNEP Centre and BNEF, 2020; IRENA and CPI, 2020) (Figure 1.6).

Global annual renewable energy investments increased almost five fold between 2005 and 2020, with solar and wind technologies recently accounting for about 90% annually.

FIGURE 1.5 **Global annual renewable energy investments by technology, 2005-2019**

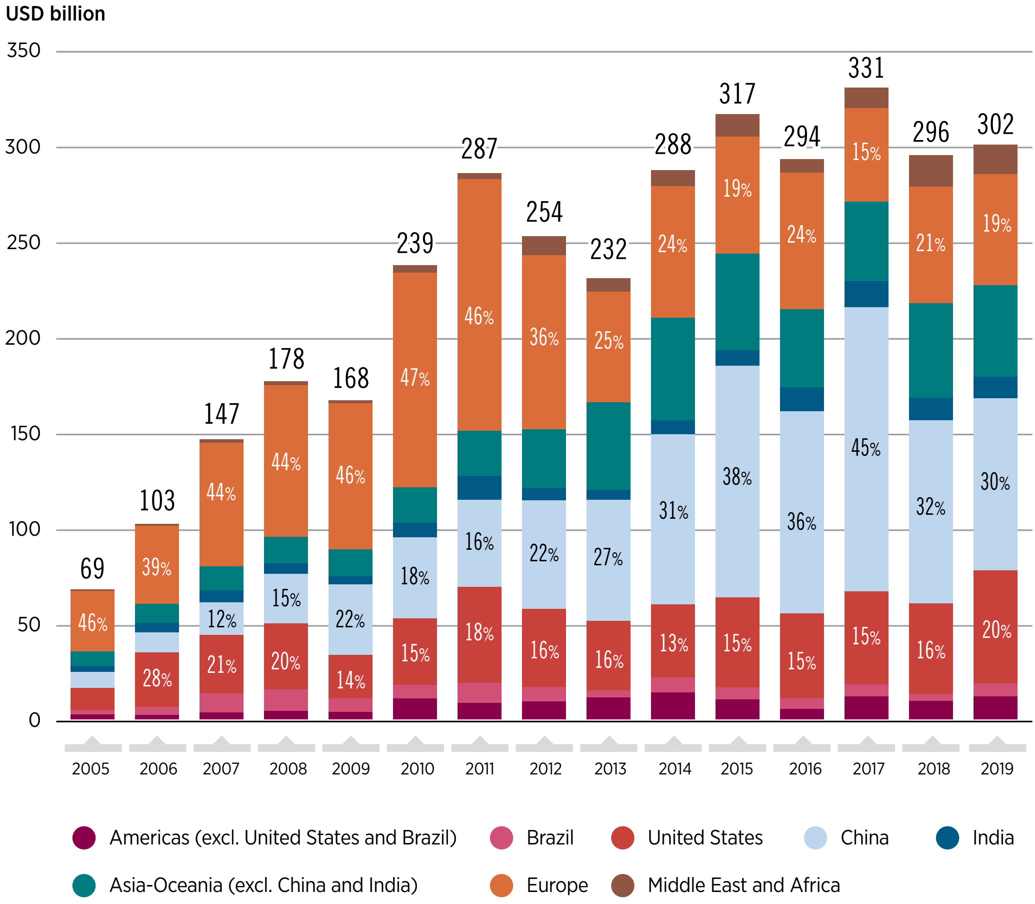


Source: Frankfurt School-UNEP Centre and BNEF 2020.

Note: BNEF data excludes investments in large hydropower (*i.e.*, greater than 50 MW), estimated at USD 28 billion on average per year between 2015 and 2019.

Annual investments in renewables remain concentrated in a handful of countries, with developing and emerging markets still attracting low levels of investments.

FIGURE 1.6 **Global annual renewable energy investments by location, 2005-2019**

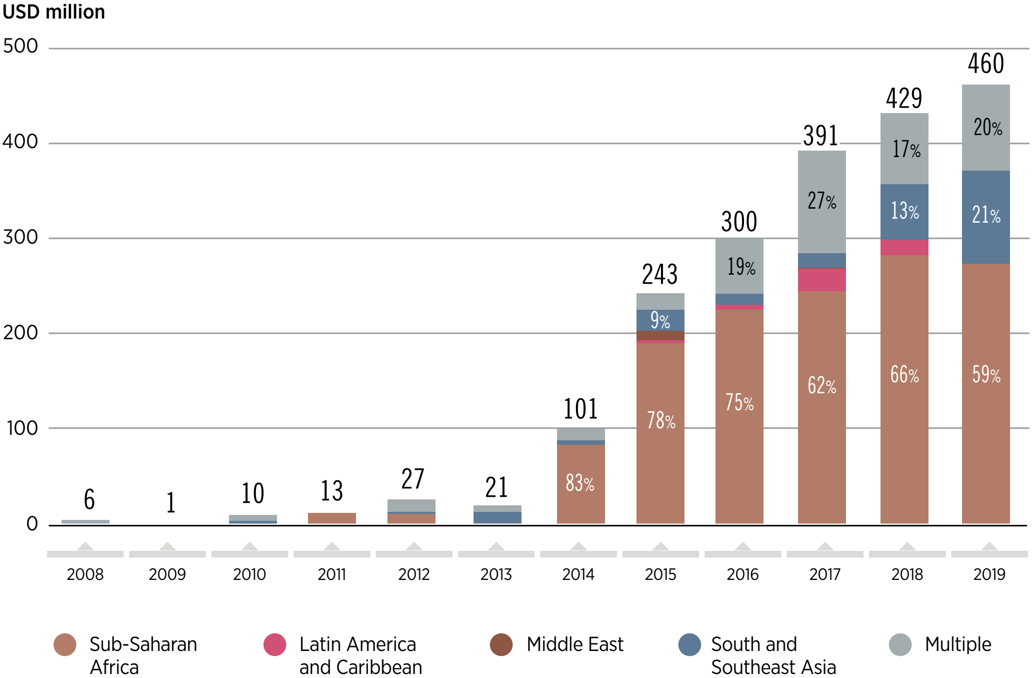


Source: Frankfurt School-UNEP Centre and BNEF 2020.

Note: BNEF data excludes investments in large hydropower (*i.e.*, greater than 50 MW), estimated at USD 28 billion on average per year between 2015 and 2019.

Annual financial commitments to off-grid renewables supporting energy access in emerging and developing countries reached USD 460 million in 2019, up from just USD 6 million in 2008. Investments remained very low until 2014 and have since grown at remarkable rates (Figure 1.7). Yet off-grid renewables still represent only 1% of the overall finance for projects to expand energy access in access-deficit countries. The majority of financing went to Sub-Saharan Africa, where 570 million people still lack access to electricity (IEA *et al.*, 2021). The region attracted 65% of cumulative investments over 2008-2019 (or USD 1.3 billion). While over half of this was directed towards East African countries, West Africa has picked up more in recent years. Solar home systems for residential use attracted the majority of investments during this period, though there is recent growth in the share of capital going to renewable energy solutions for commercial and industrial purposes (mainly mini-grids). This focus on productive uses is essential to accelerate economic growth, especially in rural areas.

FIGURE 1.7 Annual commitments to off-grid renewable energy by region, 2008-2019



Source: IRENA analysis based on Wood Mackenzie (2020).

While providing, on average, only 14% of annual investments, the public sector remains key to lower risks, overcome initial barriers, attract private investors and bring new markets to maturity.

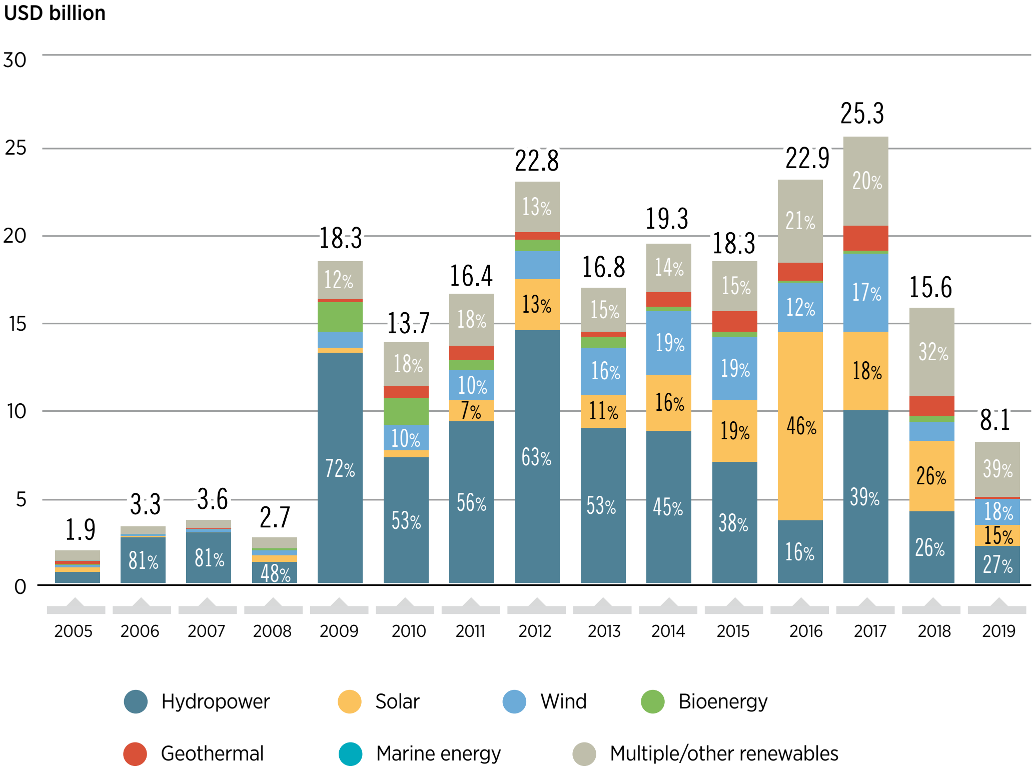
The lion's share of renewable energy financing is provided by the private sector, which accounted for 86% of investments in 2013-2018. Private capital came mainly from project developers (46%) and commercial financial institutions (22%). Institutional investors (including pension funds, insurance companies, sovereign wealth funds, and endowments and foundations), which represent a key capital pool for accelerating the energy transition, provided only a small share of total investment – 2% of total private capital in 2017-2018 (IRENA and CPI, 2020).

Globally, public finance accounts for only 14% of total direct investments in renewable energy assets. Most of this flows via development finance institutions. In addition to direct public investment in projects, considerable public resources are spent to create an enabling environment for the deployment of renewable energy through the promulgation of regulatory instruments, fiscal incentives, and other policies and measures. IRENA estimated that in Western Europe, government expenditure on measures to support renewables in 2015 was almost five times higher than direct investment in renewable energy projects (USD 66 billion as compared to USD 14 billion). When this additional expenditure is considered, the share of public financing spikes to over 55% of total renewable energy investment in 2015 in the region, compared to less than 20% if only direct public investment is considered (IRENA and CPI, 2018).

Public resources are crucial to lower risks, overcome initial barriers, attract private investors and bring new markets to maturity. As such, they play an especially vital role in emerging and developing countries where, aggravated by the COVID-19 crisis, investors' risk perception is comparatively high. As shown in Figure 1.8, public financing from development finance institutions and government agencies in these countries jumped from around USD 3 billion in 2005-2008 to USD 18 billion in 2009, and has since fluctuated, reaching a record-high USD 25 billion in 2017 before dipping in 2018 and 2019. Since 2010, public support for renewable energy in developing countries has been progressively directed away from hydropower towards less established technologies, such as solar and wind, as well as enabling infrastructure including grids and energy storage.

Beyond direct investments in projects, considerable public resources are employed for the implementation of regulatory instruments, fiscal incentives and other policies and measures in support of renewables.

FIGURE 1.8 Public annual renewable energy investments in emerging and developing countries by technology, 2005-2019



Source: IRENA, 2021c.

1.4 JOBS

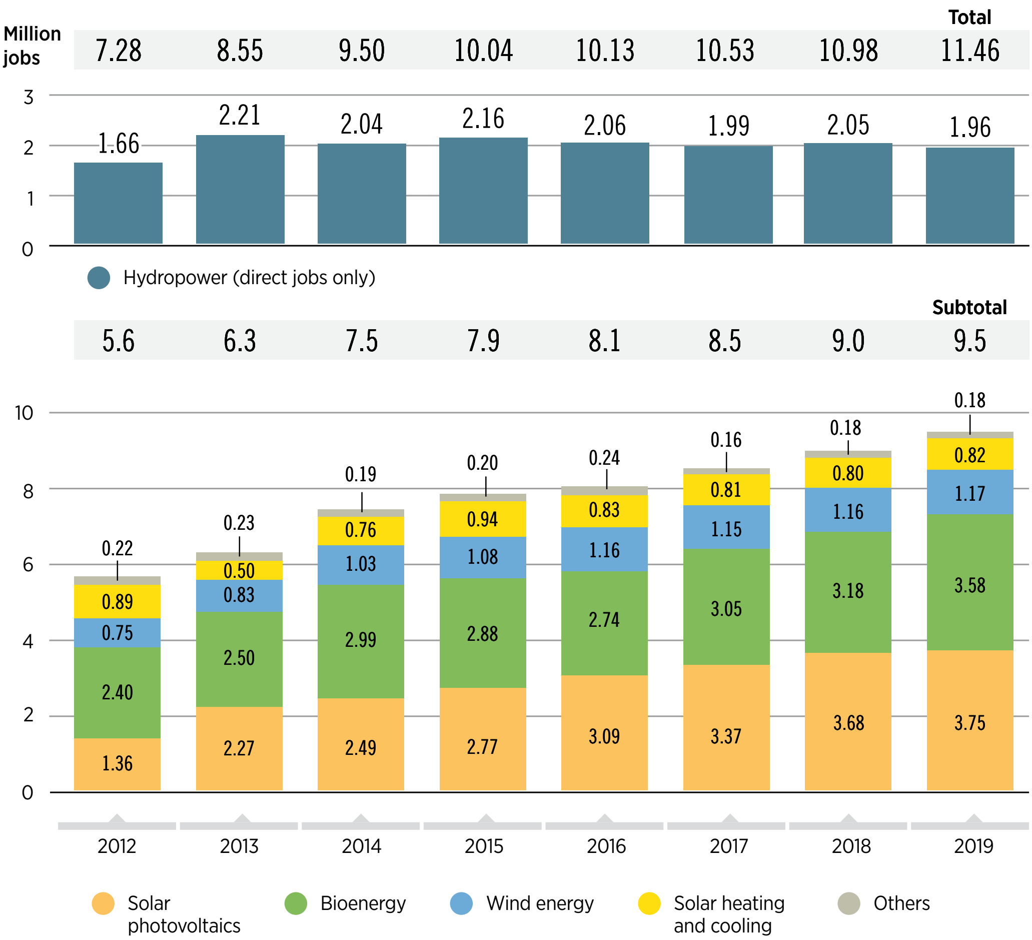
According to the most recent available estimates in 2019, the renewable energy sector worldwide employed at least 11.5 million people, directly and indirectly. The progress achieved in deploying renewable energy has yielded impressive socio-economic benefits over the past several years, including employment along the value chain. Worldwide renewable energy employment has steadily grown since 2012, when IRENA first undertook its annual assessment. That year, an estimated 7.3 million persons were employed in the sector. Figure 1.9 shows the evolution of IRENA's employment estimates, which indicate that the solar PV industry is the single-largest employer in the sector, followed by bioenergy, hydropower and wind power.

Jobs are concentrated in a number of countries that are the leading markets for the installation and manufacture of renewables-related equipment. Beyond this, jobs are being created in construction and in operations and maintenance across a wide range of countries. As countries work to leverage their domestic industries and capabilities, they may be able to generate additional employment in value-added activities in manufacturing and services.

Women comprise only 32% of the renewable energy workforce. While this is significantly higher than the 22% seen in the energy sector overall, it is evident women represent a pool of talent yet to be fully utilised.

Renewable energy deployment has created growing employment along the value chain.

FIGURE 1.9 **Global renewable energy employment by technology, 2012-2019**



Source: IRENA, 2020a.

Though renewables jobs were affected by COVID-19 as well, the sector fared better than conventional energy.

The full impact of the COVID-19 pandemic on employment in renewable energy is not yet known but jobs were affected by repeated lockdowns and other restrictions which put pressure on supply chains and constrained many economic activities. The ability of companies and industries to cope with lockdowns and supply chain disruptions differs enormously, as does their ability to switch to remote working arrangements. Renewable energy fared well compared with conventional energy, but uncertainties and disruptions dotted the way and employment impacts varied by country, renewable energy technology, segment of the renewables value chain and end-use sector. Broadly speaking, in many countries, a cycle of delays in spring 2020 was followed by great surges of activity later in the year.

Finally, indications are that employment in off-grid renewables suffered, given that capacity additions during 2020 were at a considerably lower level than in 2019, and sales of solar home systems and other solar products were at the lowest level since 2015.

These impacts reinforce the importance of a comprehensive policy framework to align short-term recovery needs with long-term decarbonisation pathways, and to ensure steady socio-economic benefits and a just transition. Deployment policies, together with enabling and integrating policies, remain essential to provide an enabling environment in which the energy transition can unfold. Paired with such measures are a set of structural policies to address challenges like fossil fuel dependence and a variety of other commodity and technological dependencies. In addition, a just transition package (including education and skill training, labour market measures, social protection, regional development efforts) can help overcome potential misalignments between job losses and gains, generate decent jobs and ensure that the energy industry workforce of the future is reflective of diversity in society offering opportunities for women, youth and minorities.

1.5 OUTLOOK FOR ACHIEVING THE 1.5°C GOAL

While the energy transition has been remarkable to date, progress falls woefully short of what is needed to limit the global temperature rise to 1.5°C by 2050. Trends to date have shown the way towards a decarbonised sector in 2050 and offered some insight into potential socio-economic impacts. But they have had little or no effect on rising emissions. Despite clear evidence of human-caused climate change, widespread support for the Paris Agreement, and the prevalence of clean, economical and sustainable energy options, energy-related carbon dioxide (CO_2) emissions increased 1.3% annually, on average, over the period 2014 to 2019. While 2020 was an outlier due to the pandemic – energy-related CO_2 emissions declined by 5.8% – a rebound looks very likely, at least in the short term (IEA, 2021a).

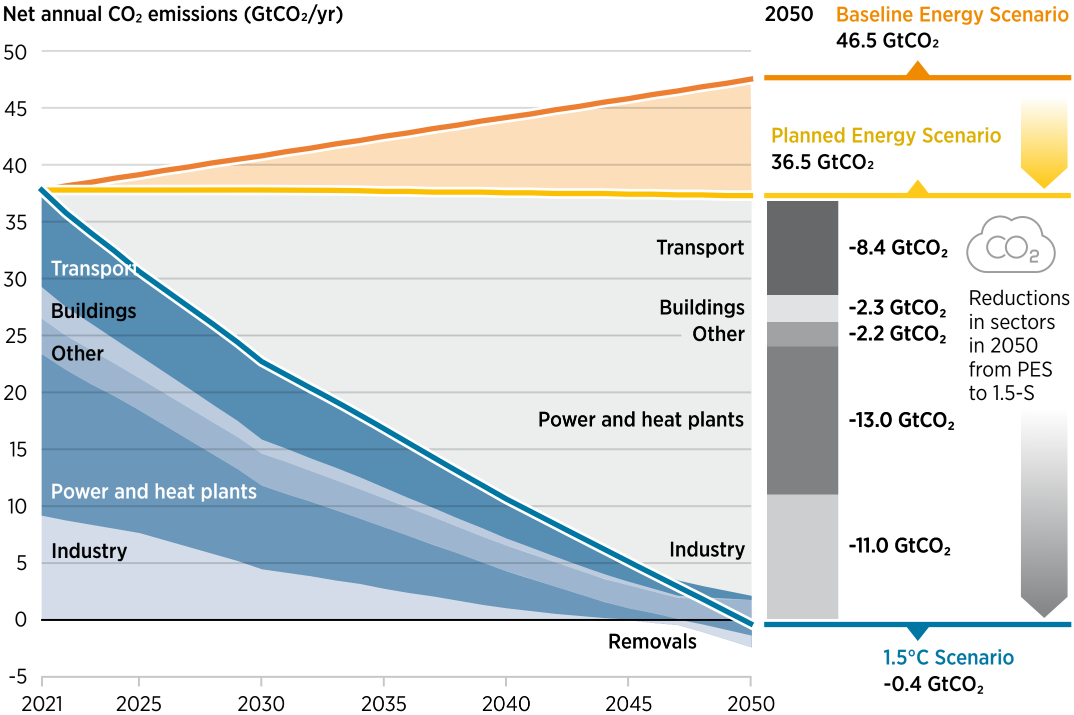
Holding the line at 1.5°C means both reaching net zero emissions by 2050 and ensuring a rapid decline in emissions, beginning now (Figure 1.10).

Under IRENA's 1.5°C Scenario, process- and energy-related cumulative CO_2 emissions from 2021 to 2050 would result in nearly 500 gigatonnes of carbon dioxide ($GtCO_2$). In alignment with the Intergovernmental Panel on Climate Change's report on limiting global warming to 1.5°C by 2050 (IPCC, 2018), IRENA plots the way to a steep and continuous downward trajectory towards a 45% decline in carbon dioxide (CO_2) emissions by 2030 and net zero by 2050. To get there, it is imperative that land-use-related emissions decline and then go negative in the years leading up to 2050 so that the overall burden on the remaining carbon budget is at least neutral.

For the moment, however, the speed of the energy transition is far from what is needed to stay in line with the Paris Agreement. Policies presently in place[3] – referred to here as the Planned Energy Scenario – would merely stabilise global emissions, with a slight drop towards 2050. Overall, the pace of future projections indicated in the Planned Energy Scenario falls far short of what is needed for a 1.5°C limit. The time dimension is crucial, and a radical shift is required, starting today, based largely on readily available renewable energy and energy efficiency technologies that can be scaled up now.

3 Based on governments' current energy plans and other planned targets and policies, including the first round of Nationally Determined Contributions under the Paris Agreement (as of 2019).

FIGURE 1.10 **Projected trends in global CO_2 emissions under three scenarios, 2020-2050**



Based on IRENA's analysis.

Note: The blue shaded areas in the figure represent the remaining net CO_2 emissions in corresponding sectors in the 1.5°C Scenario and the grey area represents the reductions in CO_2 emissions in the 1.5°C Scenario compared to the PES. Industry includes energy and process-related CO_2 emissions. International bunkers are included in transport emissions. Others include emissions from non-energy uses and other sectors such as agriculture, forestry, etc. Emissions in industry and power and heat generation plants include CO_2 emissions captured by carbon removal measures such as bioenergy with carbon capture and storage. As a result, towards 2050, these two sectors become net negative, *i.e.*, the CO_2 captured more than compensates remaining CO_2 emissions in those sectors. Overall, the net CO_2 emissions in the 1.5°C Scenario in 2050 would reach -0.4 Gt. $GtCO_2$/yr = gigatonnes of carbon dioxide per year; PES = Planned Energy Scenario.

In the Planned Energy Scenario annual emissions reach 36.5 $GtCO_2$ in 2050. For the 1.5°C Scenario, emissions need to drop to net zero by 2050.

Under the Planned Energy Scenario, annual emissions reach 36.5 $GtCO_2$ in 2050. To achieve the 1.5°C Scenario, emissions would have to drop to net zero in all sectors. Additional efforts in sectors such as power, heat and industry would be needed, with negative emissions delivering the necessary additional carbon reductions.

Aligned with the IPCC's special report on limiting global warming to no more than 1.5°C by 2050 (IPCC, 2018), IRENA's 1.5°C Scenario starts with the goal of reducing global CO_2 emissions by following a steep and accelerated downward trajectory from now to 2030 and a continuous downward trajectory thereafter, reaching net zero by 2050. Because the energy sector is currently responsible for around 80% of anthropogenic CO_2 emissions, it has a central role to play in delivering the required decarbonisation.

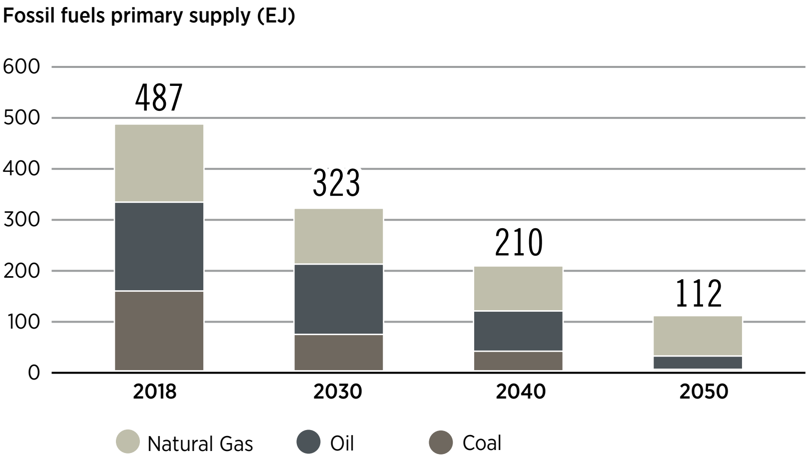
This is achievable but extremely challenging, requiring urgent action on multiple fronts. Fossil fuel use would have to decline by more than 75% by 2050 (Figure 1.11). Fossil fuels would still have roles to play, mainly in power and to an extent in industry, providing 19% of the primary energy supply in 2050. Oil and coal would drop the fastest, while natural gas would peak around 2025 and decline thereafter. The global production of oil in 2050 is expected to be 85% lower than today. Most of it would be used in industry for petrochemicals (non-energy uses, close to 40%), and in aviation and shipping. Coal production would decline even more drastically, from around 5 750 million tonnes in 2018 (160 exajoules [EJ]) to 240 million tonnes per year (7 EJ) in 2050. In the power sector, coal generation would be cut in half by 2030, in half again by 2040 and phased out by 2050. The remaining coal demand would be largely restricted to industry, mostly for steel production (coupled with carbon capture and storage) and to a certain extent in chemicals production.

Natural gas would be the largest remaining source of fossil fuel in 2050, making up 70% of total fossil fuel supply and 13% of total primary energy supply (down from 26% in 2018). In 2050, natural gas would primarily be used in industrial processes, blue hydrogen production (coupled with carbon capture and storage) and power plants.

Fossil fuel companies could more speedily shift to investing in clean energy technologies as part of their business models. Staying under 1.5°C implies that current fossil fuel investment must be halved in the coming years and decades. Planning must begin now to minimise the impact of significantly lower fossil fuel demand on the sector and related services. Indicating the importance of urgent action, IRENA (2019d) estimates that, in a pathway towards a 2°C limit, the value of assets stranded in the upstream fossil fuel sector would total USD 3.3 trillion by 2050. Delaying action could cause this value to rise to an alarming USD 6.5 trillion by 2050 – almost double. Planning in advance also supports a just transition, assisting in the reallocation and creation of jobs and services.

With accelerated uptake of renewables, fossil fuel use would drop significantly from almost 487 EJ in 2018 to 112 EJ in 2050. This implies that only a quarter of today's fossil fuel demand would remain by 2050.

FIGURE 1.11 Primary supply of fossil fuels (exajoules), 2018 to 2050, under the 1.5°C Scenario



Based on IRENA's analysis.

Fossil fuel use would have to decline by more than 75% by 2050.

1.6 CONCLUSION

Climate change, energy security, energy access and air pollution have placed a renewables-based energy transition at the forefront of the national, regional and global discourse. Addressing those problems using renewables will be indispensable if policy makers are to limit the global temperature rise to 1.5°C by 2050, with net zero CO_2 emissions. Fortunately, renewables are increasingly the lowest-cost source of electricity in many markets, capping a remarkable decade of change for renewables-based generation of electricity, during which the cost of utility-scale solar PV, for example, fell by 85%. The momentum of renewable energy is further demonstrated by its resilience in the face of the COVID-19 pandemic.

Falling costs have prompted a substantial rise in capacity, to the point where renewable power technologies now dominate the global market for new generation capacity. To meet the challenges posed by greater shares of solar and wind energy in the power mix, rapid advances have been made in digital technologies, battery storage, and new business models.

Policy instruments have evolved apace, with competitive pricing quickly overtaking administratively determined tariffs. The number of countries adopting renewable energy auction schemes increased from 16 in 2010 to 109 in 2020, driving down the average price of solar energy. The number of countries with renewable energy policies has grown as well. In 2019, 143 countries had policies for renewables in the power sector compared with 117 in 2014.

Climate change, energy security, energy access and air pollution have placed the energy transition at the forefront of the national, regional and global discourse.

In 2020, investment in the global energy transition hit a record high. Investments in electrified transport are also on the rise, as policies supporting the electrification of transport gain traction. Policies for the use of renewables in heating and cooling have received less attention, though signs of progress are abundant.

Despite their growth overall, renewable energy investments remained concentrated in a few regions and countries. The Asia-Oceania region, led by China, regularly attracts the largest share of renewable energy investment (on average, 55% during 2005-2019). Europe and the United States follow, with average shares of 20% and 16%, respectively, during 2005-2019. Regions dominated by developing and emerging economies remained consistently under-represented, attracting only about 15% of global investments. Yet, annual financial commitments to off-grid renewables supporting energy access in emerging and developing countries reached USD 460 million in 2019, up from only USD 6 million in 2008.

Overall, most renewable energy financing is provided by the private sector – 86% in 2013-2018. Private capital came mainly from project developers (46%) and commercial financial institutions (22%). To date, conservative institutional investors have provided only a small share of financing, though this is expected to change as the perceived risks of investment in renewables fall.

Although public finance accounts for only 14% of total direct investments in renewable energy assets, considerable public resources are spent to create an enabling environment for the deployment of renewable energy through the promulgation of regulatory instruments, fiscal incentives, and other policies and measures. Public financing resources are crucial to lower risks, overcome initial barriers, attract private investors and bring new markets to maturity. As such, they play an especially vital role in emerging and developing countries where, aggravated by the COVID-19 crisis, investors' risk perception is comparatively high.

The time dimension is crucial and a radical shift is required based on readily available renewable energy and energy efficiency technologies that can be scaled up now.

The progress achieved in deploying renewable energy has yielded impressive socio-economic benefits over the past several years, notably job gains all along the value chain. Most of the new jobs are found in the countries that are the leading markets for the installation and manufacture of renewables-related equipment. But employment is also being created in construction and in operations and maintenance across a wide range of countries.

The full impact of the COVID-19 pandemic on employment in renewable energy is not yet known, but renewable energy fared well compared with conventional energy. In many countries, a cycle of delays in spring 2020 was followed by great surges of activity later in the year. These impacts reinforce the importance of a comprehensive policy framework to align short-term recovery needs with long-term decarbonisation pathways and to ensure steady socio-economic benefits and a just transition.

Trends to date have shown the way towards a decarbonised sector in 2050 but they have had little or no effect on rising emissions. Indeed, progress still falls woefully short of what is needed to hold the rise in global temperature to 1.5°C by 2050. The time dimension is crucial and a radical shift is required based on readily available renewable energy and energy efficiency technologies that can be scaled up now. IRENA's 1.5°C Scenario starts with the goal of reducing global CO_2 emissions by following a steep and accelerated downward trajectory from now to 2030 and a continuous downward trajectory thereafter, reaching net zero by 2050. This is achievable but extremely challenging, requiring urgent action on multiple fronts, as explored in detail in Chapter 2.

02 TECHNOLOGICAL AVENUES TO CLIMATE TARGETS

The Paris Agreement sets out a global framework to avoid dangerous climate change by keeping global warming below 2°C by 2050, while pursuing efforts to limit it to 1.5°C. Taking the agreement as a starting point, IRENA performed an in-depth analysis to identify six components of an energy transition robust enough to meet the 1.5°C climate goal, one that is in line with other energy scenarios and studies. These components form the heart of this inaugural edition of the World Energy Transitions Outlook.

Most of the technologies needed for an energy system producing net zero emissions of carbon dioxide are already available. Although their costs must be further reduced, their deployment can be accelerated through innovations – and it is imperative to ramp up deployment now. Over 90% of the solutions required to meet the 2050 goal involve renewable energy through direct supply, electrification, energy efficiency, green hydrogen, and bioenergy combined with carbon capture and storage (BECCS).

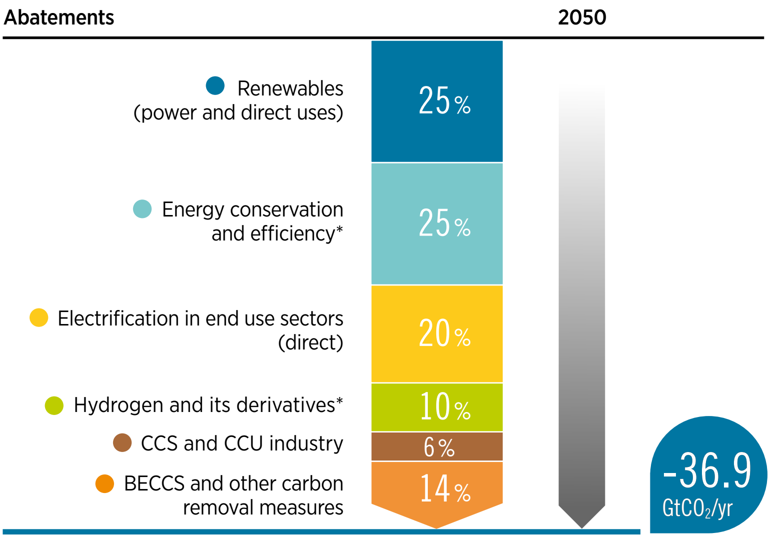
Section 2.1 provides an overview of the 1.5°C Scenario, which represents IRENA's suggested pathway toward the Paris targets. Section 2.2 highlights solutions in key technological avenues to achieve the 1.5°C climate future. Section 2.3 presents a comparison of energy scenarios from several organisations that have put forward visions of a Paris-complaint energy future.

Most of the technologies needed to reach net zero carbon emissions globally by 2050 are available today. Renewable power, green hydrogen and modern bioenergy will dominate the world of energy in the future.

2.1 CONTEXTUALISING THE 1.5°C CLIMATE PATHWAY

WETO outlines how carbon dioxide (CO_2) emissions abatements would be allocated across energy sources, practices, and uses (Figure 2.1) under the 1.5°C Scenario.

FIGURE 2.1 Carbon emissions abatements under the 1.5°C Scenario (%)



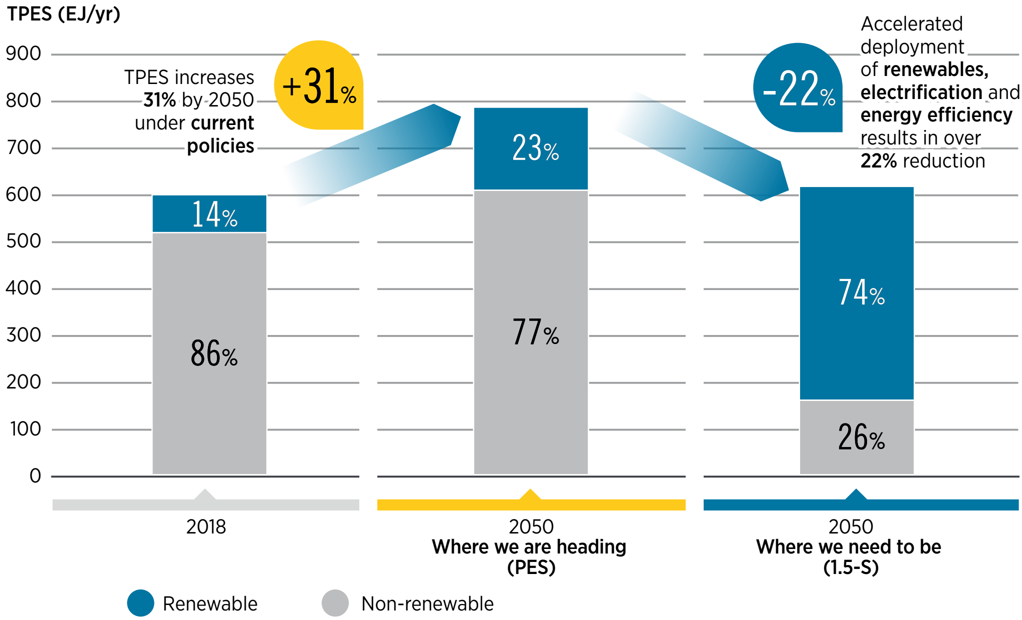
Note: Abatement estimates include energy and process-related CO_2 emissions along with emissions from non-energy use. Renewables include renewable electricity generation sources and direct use of renewable heat and biomass. Energy efficiency includes measures related to reduced demand and efficiency improvements. Structural changes (*e.g.*, relocation of steel production with direct reduced iron) and circular economy practices are part of energy efficiency. Electrification includes direct use of clean electricity in transport and heat applications. Hydrogen and its derivatives include synthetic fuels and feedstocks. CCS describes carbon capture and storage from point-source fossil-fuel-based and other emitting processes, mainly in industry. BECCS and other carbon removal measures include bioenergy coupled with CCS in electricity, heat generation, and industry.

CCS = carbon capture and storage; BECCS = bioenergy with carbon capture and storage; CCU = carbon capture and utilisation; $GtCO_2$ = gigatonnes of carbon dioxide.

Renewable energy plays a key role in the decarbonisation effort. Over 90% of the solutions in 2050 involve renewable energy through direct supply, electrification, energy efficiency, green hydrogen and bioenergy with carbon capture and storage.

Renewables, electrification and energy efficiency are the main pillars of the energy transition. The global energy transition features the synergy of two important actions: (1) the increasing use of low-cost renewable power technologies and (2) the wider adoption of electricity to power end-use applications in transport and heat. Electrification allows for the use of carbon-free electricity in place of fossil fuels in end-use applications, and significantly improves the overall efficiency of energy service supply. Electric vehicles, for instance, are more efficient than internal combustion engines. Hydropower generation, as well, is more efficient than natural gas generation. This is important as reductions in energy intensity need to be accelerated.

FIGURE 2.2 Renewable and non-renewable share of total primary energy supply in 2018 and 2050, PES and the 1.5°C Scenario (EJ/yr)



Note: Data include international bunkers and non-energy use of fuels for the production of chemicals and polymers. 1.5-S = 1.5°C Scenario; EJ/yr = exajoules per year; PES = Planned Energy Scenario; TPES = total primary energy supply.

Renewable energy's share of the world's total primary energy supply grows from 14% in 2018 to 74% in 2050 under the 1.5°C Scenario. This requires an eight fold increase in annual growth. Primary supply stabilises during this period due to increased energy efficiency and the growth of renewables.

Energy efficiency must be scaled up rapidly and substantially to meet the 1.5°C target.

The historical energy intensity improvement rate[1] is far below what is needed. For most of the past decade, energy intensity decreased by about 1.2%/year. In the 1.5°C Scenario, the rate of energy intensity improvement needs to increase to 2.9% per year, nearly two and a half times the historical trend. The energy intensity of the global economy would decline by over 60% as a result.

Energy efficiency technologies and measures are "ready-to-go" solutions, available for significant scale-up now. Energy intensity improvement can be driven by a wide range of technologies and approaches, including electrification, adoption of renewable energy generation such as solar and wind, technical efficiency improvements, and structural and behavioural changes.

A key step is the deployment of energy efficiency measures that improve technical efficiency, such as more efficient boilers, air conditions, motors and appliances. These would contribute about 38% of the reductions needed in the 1.5°C Scenario to meet the energy intensity improvement goal (corresponding to 0.65 pp per year out of the 1.7 pp per year increase needed to bring the current 1.2%/year up to 2.9%/year).

Electrifying end-use sectors using renewable power leverages synergies with energy efficiency measures and brings additional energy intensity improvements. One reason is that solar, wind and hydropower plants produce electricity that has minimal energy conversion losses (and energy intensity is based on primary energy) compared to the use of fossil fuels for electricity generation.

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

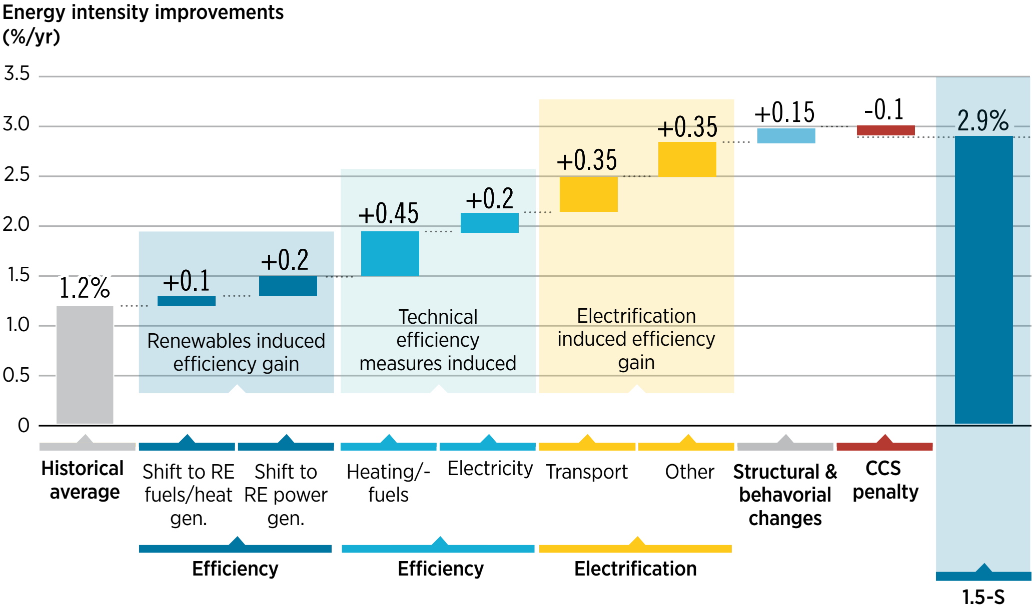
Also, electric vehicles and heat pumps are much more efficient than comparable fossil-fuel-based systems. Increased electrification reduces growth in overall primary energy use if supplied by renewable power, and allows a given amount of renewable energy to yield a higher percentage share in the energy system at the same time. This important synergy between renewable energy and energy efficiency is often overlooked and can be leveraged to address dual mandates of increasing efficiency while increasing renewable shares (IRENA, 2017).

Thus, a combination of the large-scale adoption of renewable energy technologies outlined in the 1.5°C Scenario combined with high levels of electrification result in the largest increase in the rate of energy intensity improvement. Just under 18% of the improvement (0.3 pp per year) comes from the use of renewable energy technologies such as solar, wind and hydro to supply energy for electricity and heat, as well as a shift from traditional uses of bioenergy to modern forms of renewable energy. The largest improvement, making up over 40% (0.7 pp per year), comes from electrification, such as electric vehicles in road transport and heat pumps for heating and cooling applications. In total, the combination of renewable energy and electrification makes up just under 60% of the improvement needed to achieve the scenario's energy intensity goal.

An important contribution will also come from structural and behavioural changes providing just under 10% of the needed efficiency improvement (0.15 pp per year). Circular economy principles will play an increasingly important role in forthcoming decades, furthering 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 optimise the transport of heavy goods (e.g., as efficiency enhancements in traffic control reduce the overall energy consumed by freight). Technology shifts can also lead to the relocation of industrial processes, for instance, the shift from traditional carbon and energy-intensive steel production methods to green steel production methods with green hydrogen. Electric arc furnaces could enable a wider relocation of the iron and steel sector to places where relatively low-cost and abundant renewable electricity sources are available. Such shifts could also have geopolitical and global economic implications.

Fossil fuels are still consumed in the 1.5°C Scenario, and the resulting CO_2 will need to be captured and sequestered. This process is energy intensive, pushing up energy demand. This carbon capture and storage (CCS) "penalty" reduces the energy intensity improvement by about 0.1 pp per year.

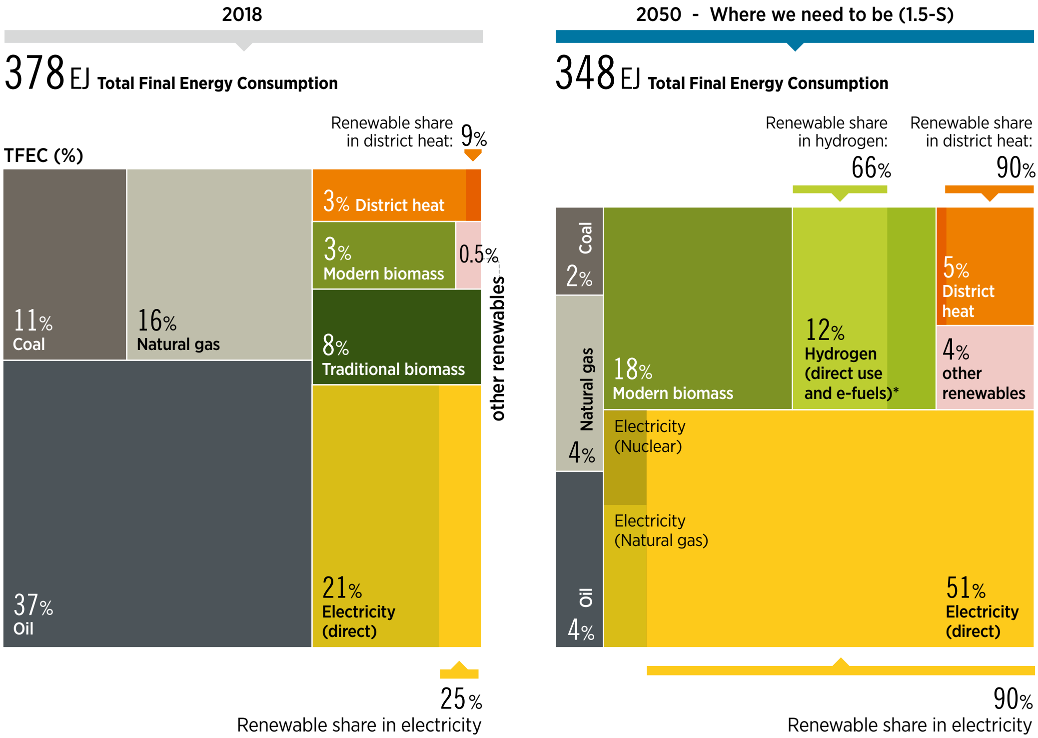
FIGURE 2.3 Energy intensity improvement rate and contributions, by category, historical and under the 1.5°C Scenario, 2018 to 2050



Note: The categories listed represent aggregate sums of measures. "Renewables induced efficiency gain" refers to energy intensity improvements achieved through the deployment of renewable technologies in the power sector (wind, solar PV, etc.) and in end-use direct applications (solar thermal, switching from traditional use of bioenergy to modern renewables, etc.). "Technical efficiency measures" include efficiency measures deployed in industry, buildings and transport sectors (*e.g.*, improving insulation of buildings; more efficient appliances, motors, etc.). "Electrification" denotes electrification of heat and transport applications such as through heat pumps and electric vehicles. 1.5-S = 1.5°C Scenario; CCS = carbon capture and storage; RE = renewable energy.

In the 1.5°C Scenario, the rate of energy intensity improvement needs to increase to 2.9% per year, nearly two and a half times the historical trend, causing the energy intensity of the global economy to fall over 60%.

FIGURE 2.4 **Breakdown of total final energy consumption (TFEC) by energy carrier in 2018 and 2050 (EJ) in the 1.5°C Scenario**



Note: The figures above include only energy consumption, excluding non-energy uses. For electricity use, 25% in 2018 and 90% in 2050 are sourced from renewable sources; for district heating, these shares are 9% and 90%, respectively; for hydrogen (direct use and e-fuels), the renewable energy shares (*i.e.*, green hydrogen) would reach 66% by 2050. The category "Hydrogen (direct use and e-fuels)" accounts for total hydrogen consumption (green and blue) and other e-fuels (e-ammonia and e-methanol). Electricity (direct) includes all sources of generation: renewable, nuclear and fossil fuel based. 1.5-S = 1.5°C Scenario; EJ = exajoule.

By 2050, electricity would be the main energy carrier with more than a 50% direct share of total final energy consumption – up from 21% in 2018. By 2050, 90% of total electricity needs would be supplied by renewables followed by 6% from natural gas and the remainder from nuclear.

2.2 ACHIEVING CLIMATE TARGETS UNDER THE 1.5°C SCENARIO

2.2.1 Renewable-powered electrification

Electricity generation must expand three fold by 2050, with renewables providing 90% of the total electricity supply.

To advance the energy transition at the pace and scale needed would require almost complete decarbonisation of the electricity sector by 2050. The transition features an important synergy between increasingly affordable renewable power technologies and the wider adoption of electric technologies for end-use applications, especially in transport and heat. Accelerated deployment of renewable power technologies driven by electrification of end-use application alone would lead to almost 6 gigatonnes (Gt) of CO_2 emissions mitigated in the 1.5°C Scenario compared to the Planned Energy Scenario (PES) in 2050.

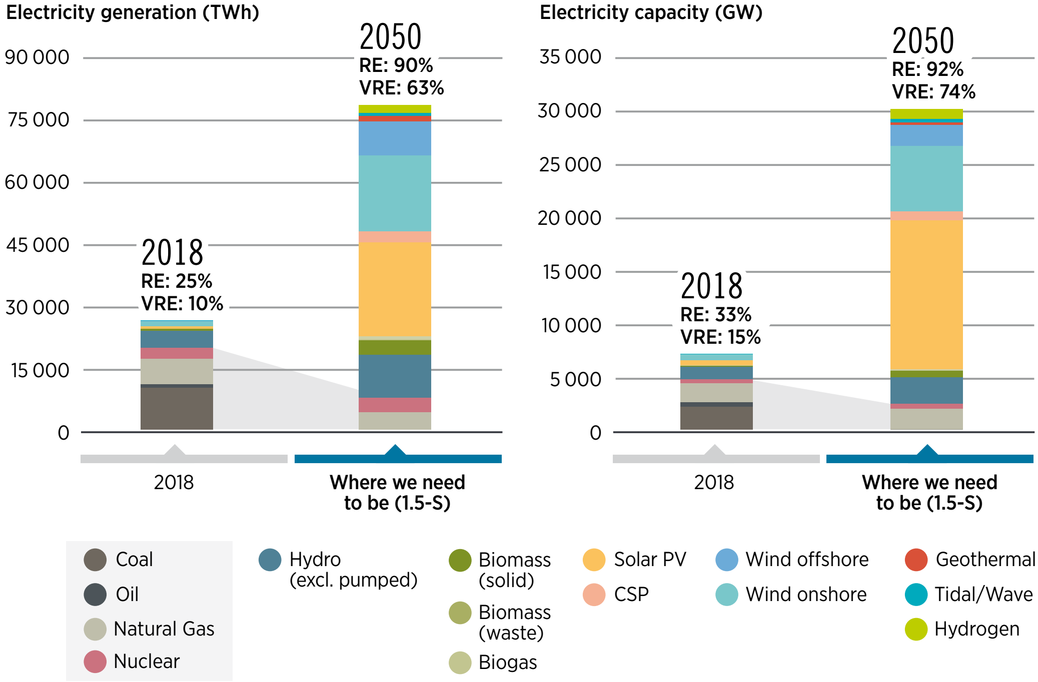
In the 1.5°C Scenario, rapid electrification of end-use applications along with the rise of green hydrogen production drive increased electricity demand. By 2050, electricity generation triples compared to the 2018 level, and renewables supply 90% of total electricity by 2050, up from 25% in 2018. Natural gas[2] (around 6%) and nuclear (around 4%) provide the remainder. Wind and solar PV lead the transformation, supplying 63% of total electricity needs by 2050; other mature renewable technologies (*e.g.*, hydro, bioenergy, geothermal) and emerging renewable technologies (*e.g.*, concentrating solar power, ocean energy) also play important roles to decarbonise the world's electricity supply. This rise is accelerated by declining costs: during their lifetime, three-quarters of onshore wind and 40% of utility-scale solar PV commissioned in 2019 produced electricity cheaper than any fossil-fuel alternatives, while three-quarters to four-fifths of the onshore wind and utility-scale solar PV commissioned in 2020 from auctions or tenders had prices lower than the cheapest new fossil-fuel-fired option.[3]

2 In the power sector, natural gas would have a role in managing demand fluctuations and providing operational reserves.

3 Based on IRENA's renewables cost database: www.irena.org/costs.

The installed generation capacity of renewable power will need to expand from over 2 800 gigawatts (GW) in 2020[4] to over 27 700 GW in 2050, about a ten fold increase. In annual terms, this requires more than 840 GW of new renewable capacity additions every year, up from around 264 GW added in 2020. Solar PV and wind (onshore and offshore) would lead the way; the installed capacity of solar PV power would reach over 14 000 GW and of wind (onshore and offshore) over 8 100 GW by 2050. Hydropower, biomass, geothermal, concentrating solar power and ocean technologies account for the remaining renewable energy expansion.

FIGURE 2.5 Electricity generation and capacity by source, 2018 and 2050 (TWh/yr and GW) in the 1.5°C Scenario



Note: 1.5-S = 1.5°C Scenario; CSP = concentrating solar power; GW = gigawatts; PES = Planned Energy Scenario; PV = photovoltaic; RE = renewable energy; TWh/yr = terawatt hours per year; VRE = variable renewable energy.

4 Based on IRENA's Statistics: www.irena.org/Statistics.

Electricity generation would grow three fold in 2050 and the share of renewables would rise to 90%. The remaining 10% of total electricity generation would be supplied by natural gas (6%) and nuclear (4%). Following a sharp decrease in coal generation over the current decade, by 2040 coal generation would be a quarter of today's level and eventually would be phased out by 2050.

To meet the 1.5°C target, no additional new coal units should be built, and the phase-out of existing ones must start now. Coal would have to be completely phased out by 2050. Nuclear power is expected to remain at an equivalent level as today. Natural gas, owing to its dispatchability, would retain a role in managing supply and demand fluctuations and in contributing to system adequacy, where hydropower and hydrogen for electricity generation are not available. Integrated energy planning and governance are key, involving system operators, energy planners, regulators, market authorities and utilities. These stakeholders should adjust codes, regulations and strategies along with needed resources. Financial markets and funds must increase shares of renewable energy in their portfolios and divest from fossil fuel investments, since meeting a 1.5°C target will have drastic implications for the business cases of these old technologies. Tax regimes, trade agreements and financial regulation must be conducive to the rapid scale-up of investment in renewable energy and energy efficiency.

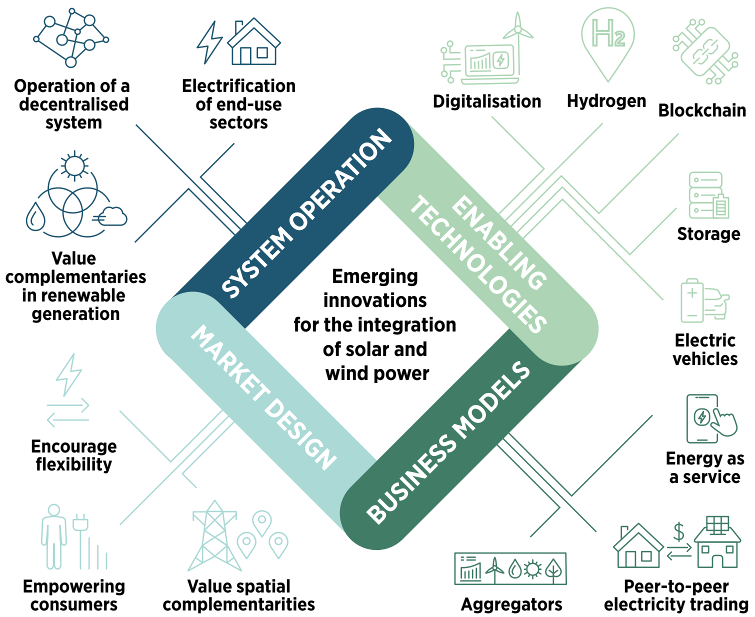
Electricity generation must expand three fold by 2050, with renewables providing 90% of the total electricity supply.

The flexibility of power systems is a key enabler for integrating very high shares of VRE – the backbone of the electricity system of the future. By 2030, the VRE share in total electricity generation would reach 42%. By 2050, 73% of the installed capacity and 63% of all electricity generation would come from variable resources (solar PV and wind), up from 15% of installed capacity and 7% of electricity generation in 2018. Such a level is manageable with current technologies leveraged by further innovations.

Several countries offer lessons in VRE integration. In 2019, VRE's share of the electricity generation mix in Denmark was over 50% (47% wind and 3% solar PV) (Business Day, 2020); it was over 40% in Lithuania and 34% in Germany (23% wind and 11% solar PV) (Renew Economy, 2019). Systemic innovations are needed that go beyond enabling technologies to encompass business models, markets and regulations, and system operations.

IRENA has identified 30 flexibility options that may be combined into comprehensive solutions, taking into account the specifics of national and regional power systems.[5] Moreover, IRENA has been analysing how power systems' organisational structures (including markets) can be redesigned to foster and support renewable-based energy (IRENA, 2020d). As more countries adopt ambitious policy targets of very high or 100% renewables, adopting such a systemic approach to innovation will become more important. The future smart power system, largely based on variable renewables such as solar PV and wind, will require significant investments in power grids and flexibility measures (*e.g.*, storage).

FIGURE 2.6 Emerging innovations that support the integration of VRE



Based on IRENA (2019a).

5 The innovation toolbox was developed in IRENA's (2019a) study, Innovation Landscape for a Renewable-Powered Future: Solutions to Integrate Variable Renewables.

IRENA has identified 30 innovations that support the integration of wind and solar PV in power systems. Innovations need to be combined as there is no "one-size-fits-all" solution and these need to be tailored to specific power systems.

On a technology level, both long- and short-term storage will be important for adding flexibility. The amount of stationary battery storage (which excludes electric vehicles) would need to expand from around 5 gigawatt hours (GWh) in 2018 to over 16 000 GWh by 2050. When the battery storage available to the grid from electric vehicle fleets is included (assuming an approximate availability factor for arbitrage), this value will increase by over 25 000 GWh to about 42 000 GWh. The production of a very large volume of hydrogen from renewable power in combination with hydrogen storage can help provide long-term seasonal flexibility starting from 2030 onwards and would provide an estimated storage capacity of 2 000 TWh by 2050). Flexibility will also be provided through additional measures, including grid expansion and operational measures, demand-side flexibility, power-to-heat and other sector coupling. Smart solutions, such as smart charging of electric vehicles, can greatly facilitate the integration of VRE by leveraging storage capacity and the flexibility potential of the demand side. Such solutions may include the following.

- **Electricity storage technologies are a critical enabler for integrating large shares of VRE into power systems,** facilitating the acceleration of the energy transition through rapid and scalable deployment and efficient provision of ancillary services, with the ability to be located virtually anywhere in the grid. Storage solutions include those offered by hydrogen, pumped hydro and batteries (including the use of electric vehicle batteries at the end of their useful lives) along with hydro, biomass and concentrating solar power thermal storage. These may be supported by digitalisation, smart communication and pricing solutions. Regulatory innovation is also essential to accommodate higher shares of VRE using storage, such as in the design and implementation of novel market mechanisms to appropriately value the essential services they provide to the system.

For example, as an alternative to physical upgrades to the infrastructure needed for the grid integration of VRE sources (*e.g.*, solar and wind), non-wire alternatives, such as utility-scale batteries connected at electricity transmission systems (also called virtual power lines) are being rolled out in several parts of the world. To make these economically attractive, market design should enable them to provide and be rewarded for a range of services including storage to reduce congestion, which would help to defer network investment, as well as ancillary and balancing services, such as frequency and voltage regulation that would support the reliable operation of the system (IRENA, 2020e).

- **Managing the loads from end-use sectors and promoting self-consumption, via distributed renewable energy sources, would help in enhancing demand-side flexibility and minimising the overall cost of system operation.** Grid expansion and reinforcement would be needed; grid codes need to be updated, and security criteria reviewed and enhanced to secure the better use of the grid. One way to accomplish these tasks is through the more dynamic application of network studies especially contingency analysis that can guarantee network security. It is crucial to expand the application of solar PV distributed solutions, moving beyond rooftop solar to consider the options of floating solar PV, embedded batteries and solar cells in appliances, buildings, street lights and other innovative applications.

  As the distinction between power-generating and power-consuming grid users blurs, it is particularly important to specify technical requirements in grid codes (Inês *et al.*, 2020), as well as for battery storage, solar PV and battery combinations, micro combined heat and power (CHP) generators, flywheels and any other combined consumer-producer connection. For example, Germany's guidelines for the low-voltage connections of distributed energy resources distinguish among facilities for consumption, generation, storage and electric vehicle charging. At medium- and higher-voltage levels, there is an additional category for mixed facilities that combine assets of multiple types (VDE FNN, 2018). One type of storage and flexibility service that deserves special mention is electric vehicle charging, because the actual storage units are not permanently connected to the facility, and the implemented functionality does not necessarily include discharging and exporting active power into the power system. This implies that grid operators need to have the technical capacity to monitor and manage so many distributed system elements.

- Another priority is to develop **innovative and alternative ways to reduce material use and reuse and recycle** components such as PV panels, wind turbines, batteries and electrolysers at the end of their lifetime (IRENA and IEA-PVPS, 2016).

- **BECCS will also be necessary to offset the remaining emissions in power and other sectors**, even as renewable capacity expansion occurs over time and coal generation is eventually phased out (by 2050).

- **Beyond technologies, innovation is needed in policies, regulations, trade agreements and business models.** Attention needs to be focused on the creation of a new market niche – the management of information and its security via smart devices – that is likely to attract investors. An energy services approach would best support the scaling up of energy efficiency measures.

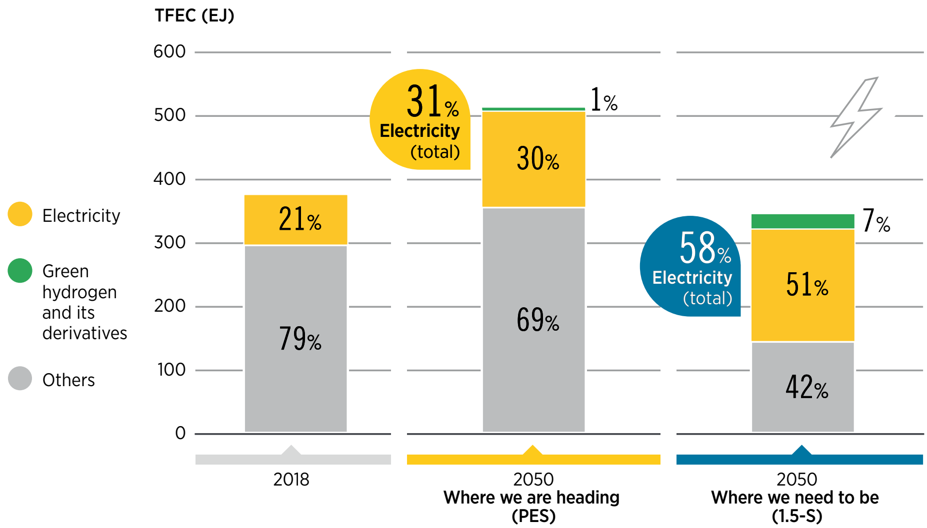
Electricity generation must expand three fold by 2050, with renewables providing 90% of the total electricity supply.

By 2050, electricity will become by far the most important energy carrier. Under the 1.5°C Scenario, electricity consumption in end-use sectors would more than double compared to 2018, reaching 50 000 TWh by 2050. Transport and hydrogen production will emerge as significant new electricity markets. In addition, around 20 770 TWh would be needed to produce hydrogen by 2050. The direct electrification share of final energy consumption (which includes direct use of electricity but excludes indirect uses such as e-fuels) would reach 30% by 2030 and exceed 50% by 2050, up from just over 21% in 2018. The use of green hydrogen and green-hydrogen-based carriers (such as ammonia and methanol) as fuels, would reach almost 2% in 2030 and 7% in 2050 from negligible levels today. In total, direct and indirect electrification would reach 58% of final demand.

The buildings sector would see the highest direct electrification rates, reaching 73% compared to 32% in 2018. A rise would also be observed in the industry sector, where the direct electrification rate would be 35% by 2050, up from 26% in 2018 (including indirect electrification, this would approach 40% by 2050). For decarbonising some heat applications, the total number of heat pumps would rise close to nine fold, exceeding 180 million by 2030 and close to 400 million by 2050 compared to around 20 million installed in 2018. More details on the technology components and pathway to decarbonise the buildings sector can be found in the annex of this report.

Electricity dominates final energy consumption either directly or indirectly, in the form of hydrogen and other e-fuels such as e-ammonia and e-methanol. Around 58% of final energy consumption in 2050 is electricity, green hydrogen and its derivatives. By 2050, electricity would be the main energy carrier with over 50% direct share in total final energy use, a rise from 21% today.

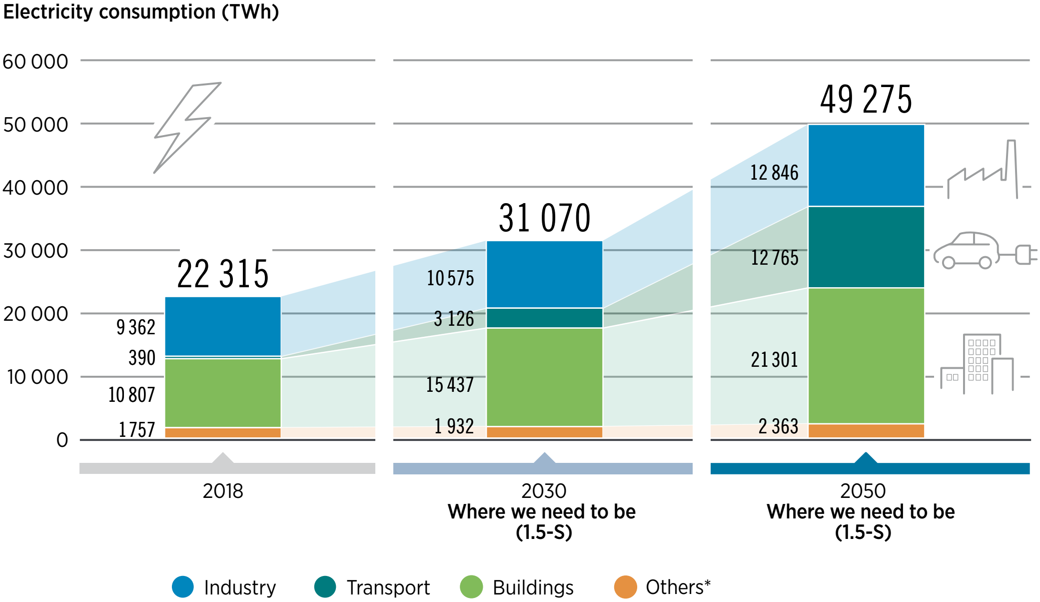
FIGURE 2.7 TFEC split by direct electricity and the use of green hydrogen and its derivative fuels, 2018 and 2050, in PES and the 1.5°C Scenario (EJ/yr)



Note: "7%" in 2050 in the 1.5°C Scenario (1.5-S) corresponds to green hydrogen and its derivatives. In addition, around 11 EJ of green hydrogen would be needed for non-energy uses in 2050 (1.5-S), which is not represented in this figure. EJ = exajoules; PES = Planned Energy Scenario; TFEC = total final energy consumption.

Transport would see the most accelerated electrification in the coming decades with the share of electricity reaching 49% in 2050, up from just 1% in 2018. The stock of electric cars would rise from 10 million in 2018 to over 380 million by 2030 and 1 780 million by 2050; the stock of electric trucks would rise to 28 million by 2050. Electric vehicles would account for more than 80% of all road transport activity by 2050 (88% of the light-duty vehicles stock and 70% of heavy-duty vehicles). This massive electrification in transport will be driven by technological progress – markedly the evolution of batteries and battery production processes – that has greatly improved the economic case for electric vehicles in recent years and is quickly expanding the scope of application to a broader set of road vehicle segments and types of services. If the ongoing cost reduction trends can be sustained, by 2050, the bulk of global road transport services could be delivered cost-effectively with electric technologies. More details on the technology components and pathway to decarbonise the transport sector can be found in the annex of this report.

FIGURE 2.8 **Electricity consumption by sector, 2018, 2030 and 2050 (TWh/yr) in the 1.5°C Scenario**



Note: Electricity use for green hydrogen is not included in the figure. By 2050, close to 21 000 TWh of electricity would be needed for green hydrogen production. 1.5-S = 1.5°C Scenario; TWh = terawatt hours.

*Others includes electricity consumption via carbon capture and storage (CCS).

Electricity demand more than doubles in 2050 compared to 2018. The use of electricity in industry and buildings double to over 12 800 TWh and 21 300 TWh, respectively and in transport it grows from nearly zero to over 12 700 TWh.

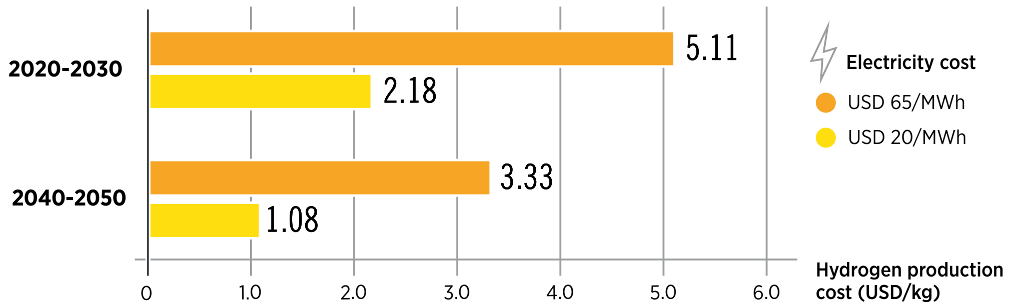
2.2.2 Green hydrogen

Hydrogen and its derivatives will account for 12% of final energy use by 2050.

As global economies aim to become carbon neutral, competitive hydrogen and synthetic fuels derived from hydrogen (such as ammonia, methanol and kerosene) emerge as key components of the energy mix. Hydrogen can help to achieve net zero CO_2 emissions in energy-intensive, hard-to-decarbonise sectors like steel, chemicals, long-haul transport, shipping and aviation. It can also play fundamental roles in balancing renewable electricity supply and demand by absorbing short-term variations as well as acting as an option for long-term storage to help balance renewable variability across seasons. In IRENA's 1.5°C Scenario, green and blue hydrogen production grows from negligible levels today to over 74 exajoules (EJ) (614 million tonnes) in 2050. In this context, hydrogen needs to be low carbon from the outset and ultimately green (produced by electrolysis of water using renewable electricity). But production costs must be cut to make it economical for countries world wide. Green hydrogen currently costs between two and three times more than blue hydrogen, which is produced using fossil fuels in combination with CCS. Falling renewable power costs and improving electrolyser technologies could make green hydrogen cost competitive by 2030.

By 2050, 30% of electricity use will be dedicated to green hydrogen production and hydrogen and its derivatives such as e-ammonia and e-methanol. Hydrogen and its derivatives together will account for about 12% of total final energy use. To produce this, almost 5 000 GW of hydrogen electrolyser capacity will be needed by 2050, up from just 0.3 GW today.

FIGURE 2.9 Hydrogen production costs resulting from low and high electricity cost assumptions



Based on IRENA (2020f).

Note: A combination of cost reductions in electricity and electrolysers, combined with increased efficiency and operating lifetime, can deliver 80% reduction in green hydrogen cost. kg = kilogramme; MWh = megawatt hour.

Green hydrogen can be produced at costs competitive with blue hydrogen by 2030, using low-cost renewable electricity.

Hydrogen will offer a solution to industry and transport needs that are hard to meet through direct electrification, mitigating close to 12% and 26% of CO_2 emissions, respectively, in the 1.5°C Scenario compared to the PES. Today, around 120 metric tonnes (Mt) (14 EJ) of hydrogen are produced annually but almost all of this comes from fossil fuels or from electricity generated by fossil fuels, with a high carbon footprint – less than 1% is green hydrogen. As electrolyser costs fall, combined with further reductions in renewable electricity costs, green hydrogen will be less expensive than the estimated cost of blue hydrogen in many locations within the next 5 to 15 years (IRENA, 2020f). In the 1.5°C Scenario, by 2050, there will be a demand for 613 Mt (74 EJ) of hydrogen, two-thirds of which will be green hydrogen. The electricity demand to produce hydrogen will reach close to 21000 town by 2050, almost the level of global electricity consumption today. This requires significant scale-up of electrolysers' manufacturing and deployment. Around 160 GW of electrolysers need to be installed annually on average up to 2050. The installation rate will start growing from a few gigawatts added per annum in the coming years and eventually ramp up from 2030 onwards, exceeding 400 GW per annum by 2050.

Priorities for technological innovation

At present, hydrogen is used at scale only in the industrial sector. Unlocking its potential across the entire energy system will require demonstration before scaling up. Some pathways, like steel production with pure hydrogen, require years of research before they reach the demonstration scale. Some parts of the hydrogen value chain are not yet cost competitive but are already deployed on a commercial scale. For instance, there are currently over 4 500 kilometres (km) of hydrogen pipelines, over 35 000 forklifts and over 25 000 passenger and commercial vehicles. Furthermore, hydrogen is already commonly used as industrial feedstock in chemical complexes and refineries. Some of the pathways and technologies that need further research are:

- **Electrolysis integration with ammonia and liquid synthesis.** These processes are mature but have been deployed separately so far; their integration remains to be demonstrated. Plant flexibility, design optimisation and operation need to be studied further. NEOM, a 2 GW electrolyser project in Saudi Arabia with a targeted start date in 2025, aims to demonstrate this concept.

- **Fuel cells for trucks.**[6] Trucks have higher durability requirements (meaning more hours of operation and cycles per year) than cars. This translates into more rare materials and a higher cost. Research is needed to achieve that high performance and durability, while still maintaining a low-cost premium for the fuel cell. This would require novel stack materials, such as catalysts, membranes and electrodes.

- **Direct reduction of steel.** This pathway is at the pilot scale today; the most advanced project is HYBRIT in Sweden aiming to have a demo plant by 2025 (HYBRIT, 2021). The direct reduction of steel is already being accomplished today based on natural gas but further research is needed to understand the operation of the shaft furnace with pure hydrogen (instead of syngas) and the effect on physical (hydrogen embrittlement, tumble, fines) and metallurgical (reducibility, metallisation, carbon) properties of the product (Ripke, 2017).

- **Ammonia-fuelled ships.** Ammonia could be used in either fuel cells or internal combustion engines. MAN ES, the largest marine engine manufacturer in the world, plans to develop the first ammonia-fuelled engine by 2024 (The Motorship, 2020). More than 50 research projects are underway looking at ammonia use in reciprocating engines. Some of the challenges are ammonia's slow flame velocity, slow heat release and low flammability. Areas for innovation are the pilot fuel requirement,[7] the use of dual-fuel engines and the reduction of nitrogen oxide (NO_x) emissions. Ammonia could also be used in fuel cells but these lack power density and load response capability, are expensive (> EUR 1 500/kilowatt) and are at an early stage of development.

- **Hydrogen ships.** Hydrogen has been used in the fuel cells of ships in only a couple of demonstration projects to date, mostly in ferries with up to 600 kW capacity. The current limit for fuel cells is around 2 MW (Trellis *et al.*, n.d.) which would be enough for a small bulk carrier, but a large container ship can be up to 130 MW (IMO, 2015). Further innovation is needed to scale fuel cells up for use in bunkering infrastructure (*e.g.*, allowing more frequent refuelling [Mao *et al.*, 2020]), and to reduce cargo displacement due to fuel storage.

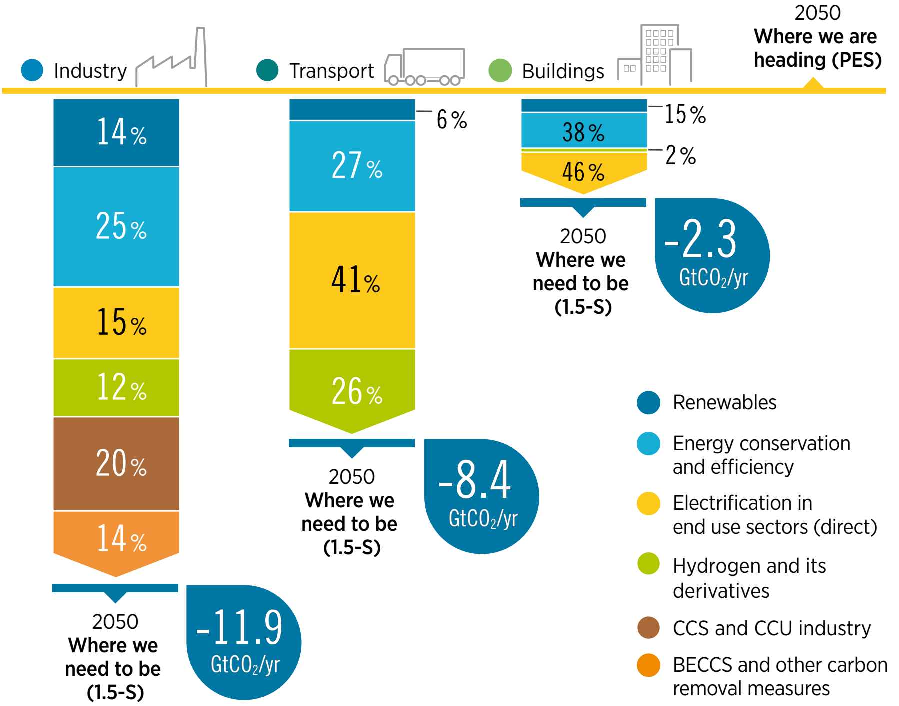
- **High-temperature electrolysis.** This technology promises high efficiency levels (> 90%) and heat integration with exothermic processes characterised by high costs and fast degradation (*i.e.*, short lifetimes). Some of the areas where further innovation is needed are the improvement of electrolyte conductivity, optimisation of chemical and mechanical stability, matching the thermal expansion coefficient to both electrodes and ensuring minimal reactant crossover (IRENA, 2020f).

- **Direct air capture (DAC).** CO_2 is needed for methanol and synthetic fuels and DAC is one of two sustainable carbon sources (along with bioenergy). There are only 15 plants around the world with a cumulative capacity of 9 000 tonnes/year (IEA, 2020c). DAC's energy consumption and cost need to come down, as they are currently in the order of 6–8 gigajoules per tonne of carbon dioxide (GJ/tCO_2) and several hundreds of US dollars per tCO_2. This could be achieved through new sorbent materials, an all-electric concept, hybrid designs for heat integration and widening the operating window of the plant to encompass a flexible electricity input (ICEF, 2018)

6 Electrification is the main decarbonisation strategy for road freight (70% of activity), but fuel cell electric trucks are still needed to cover part of the balance (13%) by 2050.

7 Ammonia has low flammability which makes the use of another fuel necessary. This could be hydrogen obtained from the ammonia itself.

FIGURE 2.10 **CO_2 emissions abatement options in the 1.5°C Scenario compared to PES in the industry, transport and building sectors.**



Note: Industry includes emissions from energy, process and non-energy uses. International bunkers are included in transport emissions. Renewables include direct use of renewables such as biomass, solar thermal and geothermal. Energy efficiency includes measures related to reduced demand and efficiency improvements. Structural changes (*e.g.*, relocation of steel production with direct reduced iron) and circular economy practices are part of energy efficiency. Electrification includes direct use of clean electricity. Hydrogen includes indirect use of clean electricity via synthetic fuels and feedstocks (*e.g.*, hydrogen and its derivates). CCS describes carbon capture and storage from point-source fossil-fuel-based and other emitting processes mainly in industry and for blue hydrogen production. BECCS and other carbon removal measures include bioenergy coupled with CCS and other measures such as reforestation and other measures in industry. CCS = carbon capture and storage; BECCS = bioenergy with carbon capture and storage; CCU = carbon capture and utilisation; $GtCO_2$ = gigatonnes of carbon dioxide; PES = Planned Energy Scenario.

In transport, 67% of emission reductions come from direct electrification and hydrogen. In industry, hydrogen and electrification combined contribute 27% of mitigation needs. In buildings, the key solutions are electrification, contributing close to half of the reduction needed, followed by energy efficiency.

Next to electricity, the direct use of renewables (bioenergy, solar thermal and geothermal) would occupy a major share (22%) of total final energy demand by 2050.
Solar thermal, geothermal and bioenergy will be needed to provide heat in industrial processes, cooking and space and water heating in buildings, and fuels for transport. In the 1.5°C Scenario the direct use of renewable energy would need to grow to 77 EJ in 2050 compared to 44 EJ in 2018. Bioenergy makes up a large share of renewable energy use today and will remain a significant source of fuel, both in industry and transport. In the 1.5°C Scenario, the share of final energy met using modern forms of bioenergy increases to 17% in 2050 from around 1.5% in 2018, requiring 153 EJ of primary biomass supply. Priorities for bioenergy include the production of advanced biofuels for aviation, road freight and shipping; the production and use of renewable fuels and feedstock for the chemical industry, and some use for heating in specific industry sub-sectors. In addition, BECCS will be used in power and heat production and some industrial processes (*e.g.*, cement and chemical production). IRENA's analysis finds that, with care, the level of primary biomass can be harvested sustainably without causing deforestation or other negative land-use changes (IRENA, 2014).

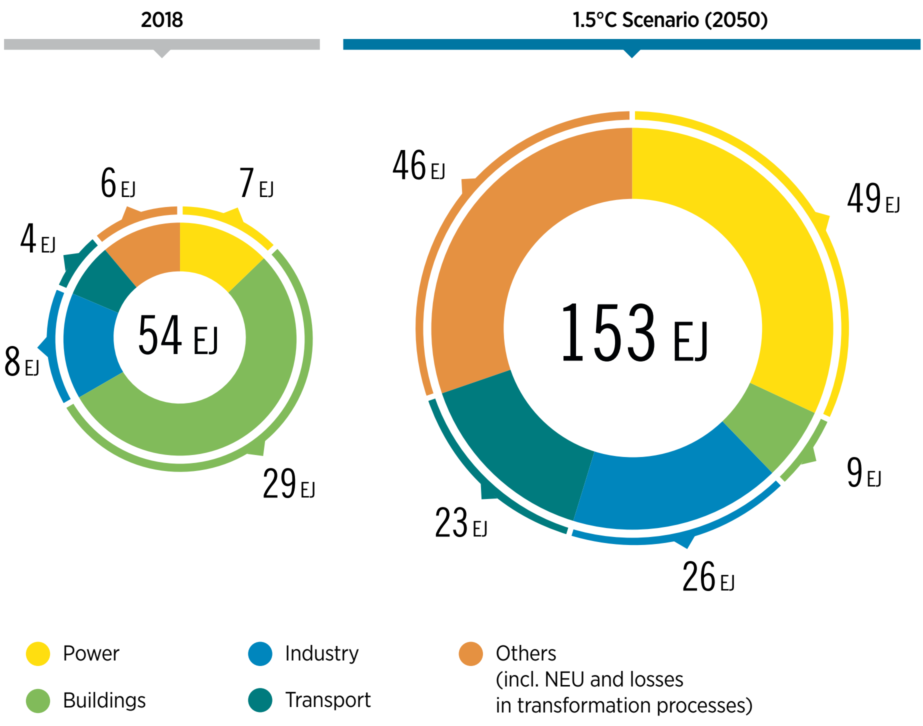
2.2.3 Modern bioenergy

Bioenergy, including solid biomass, biogas and biomethane, and liquid biofuels, would represent 25% of total primary energy supply by 2050 in IRENA's 1.5°C Scenario. That means just over 150 EJ of biomass primary supply, a three fold increase compared to 2018 levels. Without increasing biomass production and use, the 1.5°C climate goal is not achievable.

Biomass will be needed across the energy system. In some sectors it would play a major role – particularly as feedstock and fuel in the chemicals sectors and as fuel in the aviation sector. In many others it would help address gaps that other options cannot fully resolve, such as the need for biomethane to replace natural gas in buildings that cannot be renovated. Additionally, the use of biomass coupled with CCS in the power sector and some industrial sectors will be critical in delivering much needed negative emissions to achieve the net zero goal.

Given finite biomass resources, prioritisation and cross-sectoral planning will be important to ensure that appropriate biomass feedstocks are available for the appropriate applications. Innovation and scale are needed to reduce the costs and diversify the sources of supply and broaden production. For example, there is a need to further develop conversion technologies to use alternative feedstocks. However, the biggest challenges will be in scaling up production sustainably, without causing social, environmental or economic harm. The growing examples of good practice in biomass production suggest that this is possible, but regulating and managing its use such that that society can be confident in its sustainability will be challenging.

FIGURE 2.11 **Primary bioenergy demand in 2018 and 1.5°C Scenario 2050 (EJ/yr)**



Note: * The decline in bioenergy use in the buildings sector from 2018 to 2030 is due to the phase-out of traditional biomass uses in favour of modern bioenergy. EJ/yr = exajoules per year; NEU = Non-Energy Uses.

Primary bioenergy demand would grow from around 54 EJ in 2018 to over 150 EJ by 2050. Liquid biofuels consumption would reach 25% of total transport fuel demand by 2050 from 3%. Bioenergy would play an important role in electricity generation, providing thermal energy in industry and in aviation and marine energy supply by 2050.

Bioenergy makes up a large share of renewable energy use today and would remain a significant source of fuel and feedstock in IRENA's 1.5°C Scenario. Achieving the net zero goal will not be possible with renewable electricity and energy efficiency alone; bioenergy will be needed to provide heat in industrial processes, cooking and space and water heating in buildings and fuels for transport. Biomass will also be needed as feedstock in the petrochemical industry to produce chemicals and plastics.

In 2050 in the 1.5°C Scenario, the largest single use of biomass is in the power sector, but biomass contributes only a modest share of electricity production (around 13% of the total primary energy supply by 2050). The use of biomass in power is driven in part by the need for the negative emissions that BECCS can provide, and around 60% of the biomass power production will have CCS installed. BECCS will also be used in some heat plants and for some cement and chemical production.

Consistent with earlier IRENA analysis (IRENA, 2014), the required level of 153 EJ of primary biomass in 2050 can in principle be supplied sustainably without causing negative land-use changes. This is around three times the levels of supply in 2018 and at the higher end of the sustainable biomass supply potential estimated by IRENA and other institutions for 2050 (IRENA, 2014, 2016a, 2016b; Faaij, 2018). The challenge to scale up biomass production to those levels, while avoiding adverse environmental or social consequences, is significant. Robust policy frameworks for regulation, certification and monitoring, and responsible sourcing practices by industry actors need to be put in place globally to ensure that biomass supply is environmentally, socially and economically sustainable.

Large untapped potential remains. Options include:

- Greater use of food crop and forestry residues (while maintaining sufficient residues to enrich the soil and preserve biodiversity);
- Wood harvesting through sustainable forest management;
- The use of biogas from agricultural wastes such as manure and from municipal solid waste (which could also reduce emissions of methane); and
- The use of marginal or contaminated lands on which food production is impractical.

These practices would also deliver economic and social benefits to other parts of the bio-economy. The risk of poor practices remains, but evidence suggests that with sound policies, careful monitoring and control, and further innovation in supply chains the levels of biomass needed can be feasibly and sustainably produced.

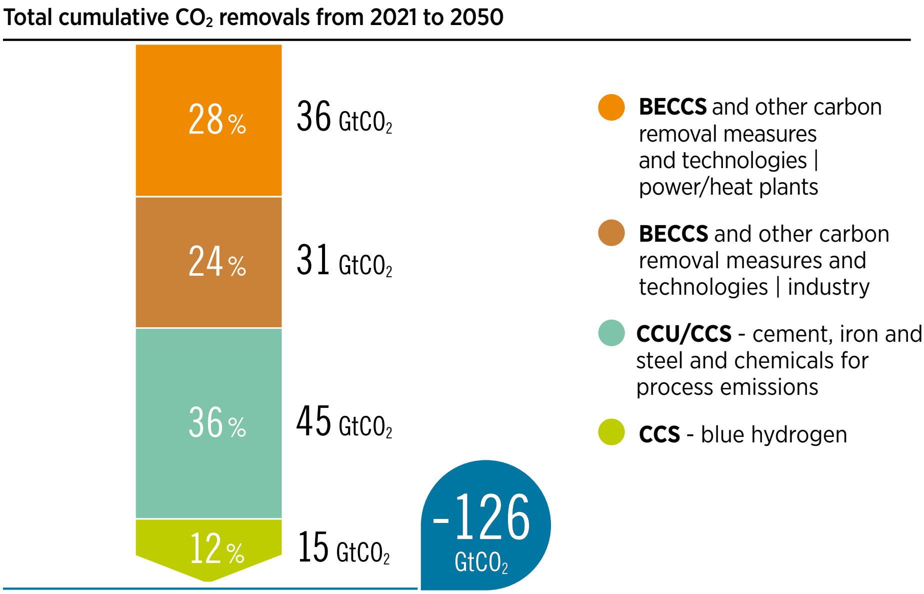
Priorities for technological innovation include the following:

- Substantial scope remains to broaden the supply of sustainable feedstocks, refine conversion technologies, decrease production costs and integrate biomass into traditionally fossil-fuel-dominated processes.
- Sustainable feedstocks need to be investigated and validated, and waste-based feedstock collection intensified. Sustainable options for growing oil-based energy crops as well as lignocellulosic conversion pathways for advanced fuels need to be pursued. These might include co-farming with other crops, seasonal (winter) farming, agro-forestry based on short-rotation woody crops, growing on degraded lands, using land made available by more intensified agriculture and using land freed up by reduced waste and losses in the food chain.
- Drop-in fuels are a key component of decarbonisation strategies for the transport sector because ethanol and conventional biodiesel have limitations on the amount that can be mixed with petroleum fuels. Innovation is needed to reduce the cost of advanced biofuels production, especially for drop-in biofuels.
- Innovation is also needed in how bioenergy and biofuels are used, in particular, the exploration of how bioenergy in CCS can be cost-effectively integrated into power and production processes.
- Beyond technological development, a systemic approach to innovation – one that pairs technology with innovations in regulatory frameworks, business models and systems operation – is critical to successfully scale up biomass use in the energy system.

2.2.4 Carbon capture and removal

Some emissions remain in 2050 from fossil fuel use and industrial processes. There will thus be a need for both CCS technologies and also CO_2 removal (CDR) measures and technologies that, combined with long-term storage, can remove CO_2 from the atmosphere, resulting in negative emissions. CDR measures and technologies include nature-based measures such as reforestation as well as BECCS, direct carbon capture and storage (DACCS) and some other approaches that are currently experimental.

FIGURE 2.12 Amount of CO_2 ($GtCO_2$) yet to be removed in the 1.5°C Scenario



Note: BECCS = bioenergy with CCS; $GtCO_2$ = gigatonnes of carbon dioxide.

In the 1.5°C Scenario, the role of CCS is limited, targeting process emissions from cement, iron and steel, hydrogen and chemical production, with a limited deployment for waste incinerators. CCS is not deployed for fossil-fuel-based power production, which would have only a marginal role by 2050. CCU applied to fossil fuel or process emissions would have only a limited role, primarily in the chemical sector. Together the use of CCS and CCU in industry and CCS for fossil-fuel-based hydrogen production expand from 0.04 Gt/year of captured CO_2 in 2020 to 2.7 Gt/year in 2040 and 3.4 Gt/year of CO_2 in 2050.

CCS & CCU technologies are in operational use, but, despite several decades of development, deployment levels are still very low. As of early 2021, 24 commercial fossil-fuel-based CCS and CCU facilities were in operation globally with an installed capacity to capture around 0.04 Gtpa of energy and process-related CO_2 emissions. Focused effort will be needed to break from the lethargic pace to date and rapidly ramp up deployments, particularly of BECCS. However CO_2 capture installations are capital intensive and have long lead times to plan, finance and build and, away from the limited existing facilities, securing support for and developing the necessary transportation and storage infrastructure can be complex and slow. Even with strengthened political and commercial support the cumulative impact of CCS & CCU this decade will likely therefore be relatively small and there is a high risk CCS, CCU and BECCS deployments will fall significantly short of the levels needed by 2030.

CDR technologies, combined with long-term storage, can in principle remove CO_2 from the atmosphere, resulting in negative emissions. BECCS is the most established option. Biomass absorbs carbon from the atmosphere as it grows and the use of CCS prevents this carbon from being released back to the atmosphere during final use, usually by storing it below ground. Provided the biomass is sustainably sourced the net result is that CO_2 is removed from the atmosphere.

In the 1.5°C Scenario, the use of BECCS in power, co-generation plants and some industrial processes (cement, chemicals, pulp mills and potentially others) would require rapid scale-up leading to 2.9 Gt/year of CO_2 captured and stored in 2040 and 4.7 $GtCO_2$ per annum in 2050, compared to less than 2 million tonnes CO_2 captured in 2020 from three operational commercial plants. Beyond BECCS, other potential CDR technologies (*e.g.*, DACCS) are mostly at an early experimental stage. Since their future potential is hard to quantify, their use is not included in the 1.5°C Scenario. As a result of the use of BECCS, in the latter part of the 2040s the power and industry sectors become net negative, *i.e.*, the CO_2 captured more than compensates the remaining CO_2 emissions in those sectors. Overall, the net CO_2 emissions in the 1.5°C Scenario reach -0.4 Gt/year in 2050.

BECCS and CCS are now established but not widely deployed or accepted technologies and the pace of progress in their development and deployment in the past decade has been very slow, much slower than many analysts predicted, with many plans falling by the wayside. If BECCS and CCS are to play an appreciable role in reaching net zero, technical, economic and social acceptance challenges will need to be addressed and the pace of development, validation and uptake will need to be greatly accelerated.

2.3 COMPARISON OF ENERGY SCENARIOS

Apart from IRENA's energy scenarios various organisations have put forward visions for the future. All of these energy scenarios, including IRENA's, propose larger renewable energy shares in primary supply compared to 2018, with nearly half of them showing lower primary supply, which indicates greater energy efficiency. Also, all result in lower emissions (Box 2.1).

While IRENA's 1.5°C Scenario as presented in this chapter sets a trajectory for the world to reach 1.5°C climate targets by reaching net zero emissions by mid-century, IRENA's Transforming Energy Scenario presents a pathway to stay well below the 2°C Paris climate target. Their solutions are largely similar though with a variation in their rate of acceleration. That said, any reductions beyond the 2°C ambition would need to consider factors such as high abatement costs (e.g., green hydrogen, BECCS); the socio-economic impacts of industry relocation; the implementation of circular economy principles and behavioural change; the availability of certain technologies at commercial scale (e.g., cement CCS, smelt reduction CCS, waste CCS, high-temperature heat pumps for industry >200°C); and the need for complex changes in existing buildings and infrastructure.

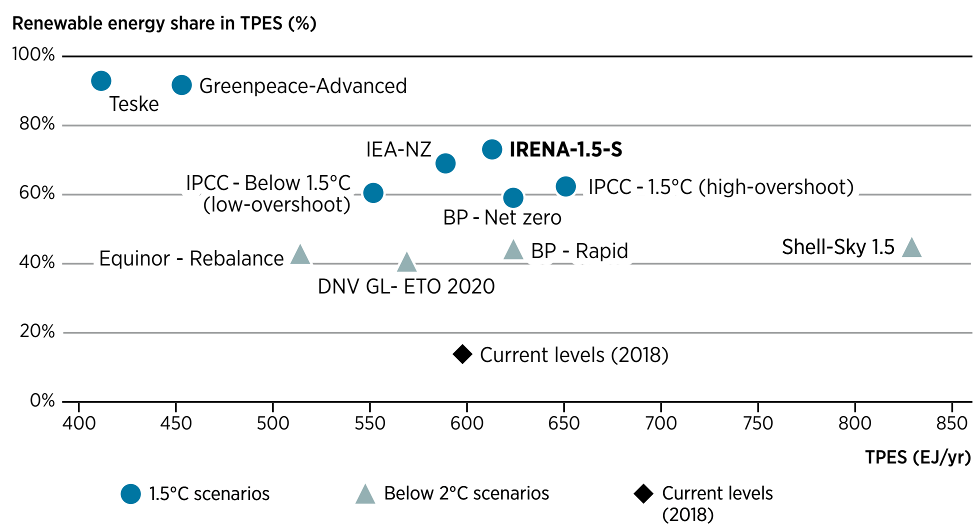
The rate of change proposed in this scenario is daunting – much of today's energy infrastructure and capital stock would need to be replaced in the next three decades to translate this vision into a reality. Ultimately, the speed and extent of the movement in this direction will determine the world's progress towards the goals of the Paris Agreement. The world needs to capitalise now on the renewed commitments made by countries and maintain the momentum, taking immediate, collaborative and concrete actions to meet the challenge of climate change (IRENA, 2021d).

BOX 2.1 Scenario comparison

Beyond IRENA's 1.5°C Scenario, several other scenarios have been published to explore pathways for the energy transition in the coming decades. Their variation reflects the complexity and uncertainties of the energy transition and different approaches and assumptions regarding the development of key components such as renewable energy and electrification as well as differences in overall carbon budgets.

Two below-2°C scenarios, DNV GL and Equinor, predict a fast transformation of the global energy sector. Though they reach similar electrification shares (35% for DNV GL and 37% for Equinor) by 2050, they have different global-energy-related CO_2 emissions, 17 gigatonnes (Gt)/year for DNV GL and 10.6 Gt/year for Equinor by 2050. Among those scenarios claiming compatibility with the

FIGURE 2.13 Shares of renewables in total primary energy in 2018 and 2050 in various energy scenarios

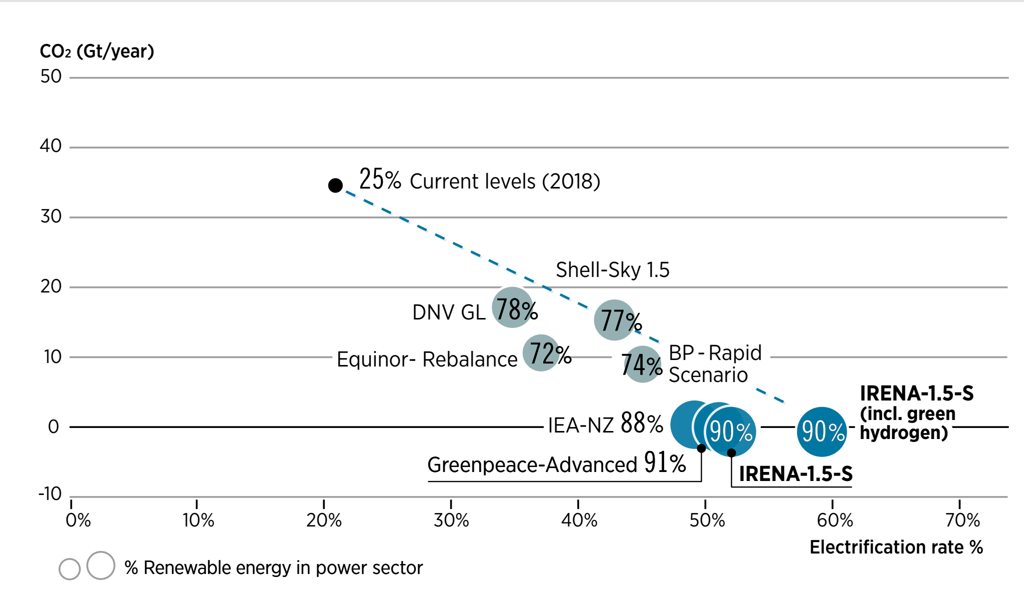


Sources: Shell's 2021 "Sky 1.5" scenario (Shell, 2021); BP's "Rapid Scenario"(BP, 2020); the "Below 1.5°C" and "Above 1.5°C" scenario from the Intergovernmental Panel on Climate Change (IPCC, 2018); Greenpeace's 2015 "Advanced" scenario (Greenpeace, 2015); Teske's "Achieving the Paris Climate Agreement Goals" (Teske, 2019); Equinor's "Rebalance scenario" (Equinor, 2020); DNV GL's Energy Transition Outlook 2020 (DNV GL, 2020) and IEA's Net Zero by 2050 (IEA, 2021b).

Note: The figure includes 2018 and 2050 projections from various energy scenarios aligned with Paris climate targets from different institutions. IPCC's (2018) special report on global warming of 1.5°C assessed several energy scenarios from different institutions and aggregated them into two 2°C and three 1.5°C pathway classes. Of these, the assessed "below 1.5°C" and "1.5°C-low-overshoot" pathways have a mean total primary energy supply equal to 553.23 EJ with a range between 289.02 EJ and 725.40 EJ (derived from the IPCC's SR15 2018 report, page 132, Table 2.6) in 2050. The mean share of renewables in total primary supply in those pathways is 60.24% with a range between 38.03% and 87.89%. For the "1.5°C-high-overshoot" pathway, the mean primary supply is 651.46 EJ (1012.50 EJ, 415.31 EJ) and the share of renewables in primary supply is 62.12% (86.26%, 28.47%). $GtCO_2$ = gigatonnes of carbon dioxide; IPCC = Intergovernmental Panel on Climate Change; TPES = total primary energy supply.

Paris climate target of staying under a 2°C temperature rise, the electrification share in 2050 varies substantially as well, from 45% in BP's "Rapid" scenario to 52% in the Greenpeace "Advanced" scenario. There is however a broad consensus on the central role that renewables would play in electricity generation with percentages ranging from 72% in Equinor's "Rebalance" scenario to 90% in IRENA's "1.5-S" scenario. Despite the differences among the energy scenarios, there is a clear consensus on the important role that electrification powered by renewable energy sources has in the decarbonisation of the energy system. With a share of 51% of direct electrification and 58% if green hydrogen and its derivates are included, coupled with 90% of renewables in the power sector in 2050, IRENA's 1.5°C Scenario shows a higher electrification rate than the other scenarios.

FIGURE 2.14 **CO_2 emissions versus electrification rates in various energy scenarios**



Note: The size of the bubbles in the figure and the number indicated beside the scenario description reflect the share of renewables in the power sector in various scenarios. 1.5-S = 1.5°C Scenario; CO_2 = carbon dioxide; Gt = gigatonne.

2.4 CONCLUSION

A net zero carbon future by 2050 may seem a daunting challenge. But IRENA's analysis indicates that it is feasible. Achieving it will require a massive ramp-up of efforts on seven fronts:

1. The rate of decline in energy intensity must move from the 1.2% recorded in recent years to 3%. Here, renewable power, electrification and circular economy principles have key roles to play, as do conventional energy efficiency technologies.

2. Annual growth in renewable energy's share in the globe's primary energy production needs to accelerate eight fold from its share in recent years.

3. Renewable power generation capacity must grow from over 2 800 GW today to 27 500 GW by 2050, or 840 GW per year and a four fold increase in the annual capacity additions recorded in recent years.

4. Electric vehicle sales must grow from 4% of all vehicle sales today to 100%, with the stock of electric vehicles growing from 7 million in 2020 to 1.8 billion in 2050.

5. Hydrogen demand must increase from 120 Mt to 614 Mt in 2050, a five fold increase. The share of clean hydrogen in overall demand needs to grow from 2% to 100%. Two-thirds of demand would be met by green hydrogen; one-third by blue. Meeting that goal will require the addition of 160 GW of electrolysers each year between now and 2050, from the 2020 base of 0.3 GW of installed capacity.

6. The total primary supply of biomass needed to achieve net zero emissions by 2050 would be just over 150 EJ, a near tripling of primary biomass use in 2018. Based on a detailed assessment of the potential supply of sustainable biomass, this appears feasible.

7. Carbon capture and storage must grow from 0.04 Gt captured in 2020 to 7-8 Gt in 2050, with BECCS accounting for half for the total amount captured and stored.

All of these challenging steps must be put in place simultaneously in order to stay within the globe's carbon budget. Such a profound transition entails accelerating the scale of energy investments – starting today – and diverting investments away from fossil fuels towards energy transition technologies such as renewables, energy efficiency and electrification of end uses – plus associated infrastructure. These investment needs are analysed in Chapter 3.

03 INVESTMENT NEEDS AND FINANCING FOR THE ENERGY TRANSITION

Funding the energy transition at the pace required to keep the world on a climate-safe pathway will require a substantial increase in investments over their current level and over the level envisaged in governments' current plans. Fortunately, the necessary funding is available in today's capital pools. The climate-safe pathway will also require a reallocation of capital towards sustainable solutions, an even greater activation of the private sector and expanded use of debt financing. The required shifts are entirely achievable. However, policy support in the energy sector and beyond remains crucial to keep the pace of the energy transition on track with global climate goals.

Government plans in place today (outlined in the Planned Energy Scenario, or PES) call for investing almost USD 98 trillion in energy systems over the next three decades. IRENA's 1.5°C Scenario could be achieved by adding USD 33 trillion to the amounts already planned, for a total investment of USD 131 trillion over the next 30 years. More than 80% of the total – USD 116 trillion through 2050 – needs to be invested in energy transition technologies (excluding fossil fuels and nuclear) such as renewables, energy efficiency, end-use electrification, power grids, flexibility innovation (hydrogen) and carbon removal measures. Cumulative investments of more than USD 24 trillion should be redirected from fossil fuels to these energy transition technologies over the period to 2050.

On average, USD 4.4 trillion would be needed annually over the period 2021-2050, more than double the level of investment in 2019 (USD 2.1 trillion) and a third more than the USD 3.3 trillion per year called for in the PES (BNEF, 2021a; IEA, 2020a; IRENA and CPI, 2020). While the amount of funding needed is large, it represents only about 5% of global gross domestic product (GDP) in 2019 and is well within the current capacity of global financial markets, which reached a volume of some USD 200 trillion in 2019 (World Bank, 2019a; SIFMA, 2020). Global institutional investors alone manage about USD 100 trillion in assets and have so far largely remained on the sidelines of the energy transition (IRENA, 2020g).

Section 3.1 of this chapter details the investment needs, by technology, for a 1.5°C climate pathway, comparing it with current plans (PES). Section 3.2 presents types of funding sources as the energy transition goes through stages of the technology revolution. It describes the key changes in funding structures to 2050 in terms of capital sources (public and private) and types of capital (equity and debt), demonstrating that the financial capital needed for the 1.5°C Scenario is available and the required shift in investments is achievable.

A climate-safe pathway requires a large scale up of energy system investments – which the world's current capital markets can provide.

Sections 3.1 and 3.2 suggest an important redistribution of investments by energy technology, as investments pour into transition-related technologies. They also show a shift in funding sources and financing structure, with private capital and debt financing playing an increasingly prominent role. As returns from fossil fuel assets become increasingly uncertain and governments around the world are announcing ambitious climate commitments and green recovery plans, investors' appetite for fossil fuel assets is expected to continue to fall - and the cost of financing for these technologies to increase. Larger shares of private capital can be expected to flow towards energy transition technologies as they further grow and gain market shares with capital markets followed by institutional capital playing a growing role.

Such changes are already underway as part of an ongoing technological revolution – but the "natural" pace is not rapid enough. While the energy transition is gaining momentum, the immediate climate emergency demands a faster pace of change. Past technology revolutions took about fifty years and the affected technology and the available financial stock were far smaller than today's. Markets alone are not likely to move rapidly enough to take transition technologies up the development curve at the pace needed. Moreover, they are likely to continue to drive investment towards regions and countries where the transition has already taken off, while areas with high real and perceived risks could be left behind. In addition, as the transition progresses, new trends and challenges will arise. While these trends will vary significantly across countries and technologies, they are likely to shape risk perception, thus affecting the availability and cost of capital. These trends are discussed in Section 3.3.

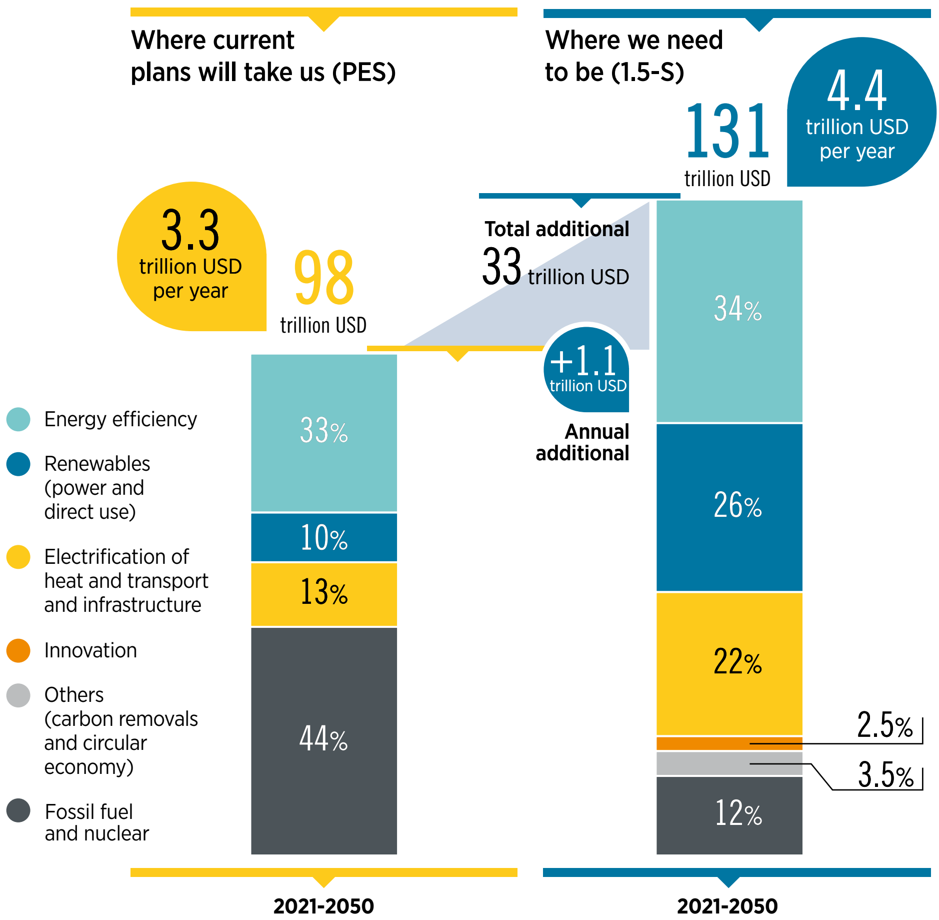
To speed up the transition to the pace needed, to drive investments to countries and regions where they would not typically flow or to overcome new challenges as the transition progresses, government intervention remains crucial to hasten the energy transition along the curve of technology development and to address the unique challenges the current transition brings. Chapter 4 describes in detail a comprehensive set of policy measures that governments can deploy to support the energy transition.

3.1 NEW INVESTMENT PRIORITIES IN THE 1.5°C SCENARIO

Ensuring a sustainable, climate-safe future calls for the scale-up of investment from the currently planned USD 98 trillion between 2021 and 2050 (under PES) to USD 131 trillion (under the 1.5°C Scenario) between now and 2050 – an incremental increase of 34%. The 1.5°C Scenario would require an additional USD 1.1 trillion per year over the PES (Figure 3.1), plus the redirection of investments from fossil fuels towards energy transition technologies (renewables, energy efficiency, and electrification of heat and transport). High upfront investments are critical mainly to enable the accelerated deployment of key renewable energy technologies in the power sector; a massive scaling up of electrification of transport modes and heating applications, along with an expansion of accommodative infrastructure; and large-scale green hydrogen projects.

For a climate-safe energy future, energy investments need to shift to low-carbon energy transition solutions and increase 34% overall compared to planned investments.

FIGURE 3.1 **Total investment by technology: PES and 1.5°C Scenario (2021-2050)**



Accelerating the pace of the energy transition and scaling up investments in energy transition technologies in all sectors hinges on what the world does between 2021 and 2030. Setting the right investment priorities is key.

In the 1.5°C Scenario, markedly more funding would be channelled to energy transition technologies compared with PES. Under the 1.5°C Scenario, renewable energy investments in both power and end uses (such as transport and heating) would reach USD 1.3 trillion annually up to 2030, and USD 1 trillion in the 2031-2050 period – more than triple the investments in 2019 and under PES. At the same time, investment in fossil fuels and nuclear technologies would peak at USD 970 billion per year up to 2030 before falling to USD 290 billion thereafter, as the ability of these technologies to attract funding falls. Under PES, they continue to account for a large but shrinking share of annual energy sector investment (USD 1.7 trillion in 2021-2030; USD 1.3 trillion in 2030-2050, respectively).

In the **power sector**, accelerated investment of USD 1.7 billion per year would account for 44% of the total required energy transition investment over the period to 2050. Investments would be directed towards additional renewable power generation capacity, grid extension and resiliency, and other grid flexibility measures (from better renewable power generation forecasting to integrated demand-side flexibility and stationary battery storage). Key generation technologies, such as solar PV (rooftop and utility scale) would draw annual average investment of USD 237 billion per year; onshore wind, USD 212 billion per year; and power grids, including energy flexibility measures, close to USD 733 billion per year. Figure 3.2 shows the annual average investments in power and end uses, both between 2017 and 2019, and as needed to fulfill the 1.5°C Scenario between 2021 and 2050.

FIGURE 3.2 **Annual average investments in power and end uses, historical (2017-2019) and needed to meet 1.5°C Scenario (USD billion/year)**

Power

		Annual average investments USD billion/yr: Historical 2017-19	Annual average investments USD billion/yr: 1.5°C Scenario 2021-50
Power generation capacity	Hydro - all (excl. pumped)	22	85
	Biomass (total)	13	69
	Solar PV (utility and rooftop)	115	237
	CSP	3	84
	Wind onshore	80	212
	Wind offshore	18	177
	Geothermal	3	24
	Marine	0	59
Grids and flexibility	Electricity network	271	600
	Flexibility measures (*e.g.* storage)	4	133

Continues next page

Note: **Power generation capacity:** Deployment of renewable technologies for power generation. **Grids and flexibility:** Transmission and distribution networks, smart meters, pumped hydropower, decentralised and utility-scale stationary battery storage (coupled mainly with decentralised PV systems) and hydrogen for seasonal storage. **Renewables direct uses and district heat:** Renewables in direct end-use and district heat applications (*e.g.*, solar thermal, modern bioenergy). **Energy efficiency in industry:** Improving process efficiency, demand-side management solutions, highly efficient energy and motor systems, and improved waste processes. **Energy efficiency in transport:** All passenger and freight transport modes, notably road, rail, aviation and shipping. Key efficiency measures include light-weight materials, low-friction designs, aerodynamic improvements, among others. Vehicle stock investments are excluded. **Energy efficiency in buildings:** Improving building thermal envelopes (insulation, windows, doors, etc.), deploying efficient lighting and appliances, equipping smart homes with advanced control equipment, replacing less efficient buildings with energy-efficient buildings. **Hydrogen electrolyser and infrastructure:** Electrolyser capacity (alkaline and polymer electrolyte membrane) for the production of green hydrogen and infrastructure for the transport of hydrogen. **Bio- and hydrogen-based ammonia and methanol:** Production of ammonia and methanol from biomass and hydrogen feedstocks. **Carbon removals:** CCS deployment, mainly for process emissions in industry and blue hydrogen production. BECCS deployment in cement and power and cogeneration plants. **Circular economy:** Material and chemicals recycling and bio-based alternative products (*e.g.*, bioplastics).

BECCS = bioenergy with CCS; CCS = carbon capture and storage; CSP = concentrated solar power.

End uses and district heat

Annual average investments USD billion/yr

		Historical 2017-19	1.5-S 2021-50
Renewables end uses and district heat	Biofuels - supply	2	87
	Renewables direct uses and district heat	31	84
Energy efficiency	Buildings	139	963
	Industry	45	354
	Transport	65	157
Electrification	Charging infrastructure for electric vehicles	2	131
	Heat pumps	12	102
Innovation	Hydrogen - electrolysers and infrastructure	0	116
	Hydrogen-based ammonia and methanol	0	45
	Bio-based ammonia	0	22
	Bio-based methanol	0	12
Carbon removals	Carbon removals (CCS, BECCS)	0	65
Circular economy	Recycling and biobased products	0	25

Total average investments
(excluding fossil fuel and nuclear)
2017-2019

824 USD billion/year

Total average investments
(excluding fossil fuel and nuclear)
2021-2050

3 843 USD billion/year

Investment in energy transition technologies needs to more than quadruple in the 1.5°C Pathway compared to the current and business-as-usual levels.

Under the 1.5°C Scenario, the **buildings** sector would require investment in a wide range of renewable and energy efficiency technologies. The solutions are varied, including LED lamps, more efficient appliances, efficiency-oriented retrofits of building shells, heat pumps and smart home systems. The average annual investment needed in the buildings sector (USD 1.09 trillion) is dominated by energy efficiency investment (USD 0.96 trillion); the remainder going for heat pumps and uses of other renewables, largely solar thermal. Overall, the buildings sector represents almost 28% of the total energy transition investment over the period to 2050.

Transport investments would rise to USD 375 billion per year (10% of total transition-related investment), excluding the incremental costs of electric vehicles. Energy efficiency measures would account for almost 42% of the total. Charging infrastructure would represent 35%; biofuel supply, 23%. Vehicle charging stations, in particular, would enlarge their share of energy sector investments to 2% up to 2030 and 4% in the period 2031-2050.

To realise the 1.5°C Scenario, it will be necessary to expand and broaden biomass supply chains while ensuring their sustainability, and to enhance and scale up conversion technologies. **Bioenergy** investments would rise to USD 226 billion per year (6% of total transition-related investment), most of it to increase the biofuels supply, while USD 69 billion per year would be needed for the bioenergy-based power generation capacity. The remaining USD 72 billion per year would be needed for the direct use of bioenergy in end-use sectors (USD 21 billion), district heat generation, production of ammonia and methanol from biomass (USD 36 billion), and deployment of bio-based plastics and organic materials (USD 13 billion) as part of circular economy practices.

Innovations will be needed in the end-use sectors and for sector coupling. Investments in electrolysers to produce **green hydrogen,** hydrogen supply infrastructure, and renewables-based hydrogen feedstocks for chemical production would exceed USD 160 billion per year on average through 2050. Because of the early stage of development of green hydrogen, supply chain investments of around USD 5 billion per gigawatt of supply (representing around 15-20 petajoules/year, enough to make 2 million tons of iron and steel or to heat half a million energy-efficient homes) would be required. Today only 0.3 GW of hydrogen electrolyser capacity is in place; manufacturing capacity is below 2 GW per year.

In the 1.5°C Scenario, thanks to a supportive regulatory framework, **new energy transition technologies** become competitive and reach scale, drawing in an increasingly large amount of new investment. Heat pumps, smart meters, energy storage, hydrogen electrolyser and networks, carbon capture and storage, bioenergy with carbon capture and storage (BECCS), and others (materials recycling, bioplastics, etc.) would account for 8% of total energy sector investments during 2021-2030 and grow to 14% in the period 2031-2050, compared with 2.2% and 1.9%, respectively, in the PES. Around USD 65 billion per year would be needed for the deployment of carbon capture and storage, mainly in industrial processes, blue hydrogen production, and BECCS for power, heat generation and industrial processes, along with infrastructure for transport and storage.

District heating and cooling systems offer the opportunity to integrate bioenergy, geothermal and solar heat. This field of investment can be combined with building renovation. Investments for deploying renewable technologies to produce district heat could be increased to around USD 8 billion per year.

Supportive policies in the 1.5°C Scenario enable the development of new energy technologies which under Planned Energy Scenario remain relatively subdued.

3.2 FUNDING STRUCTURES FOR A CLIMATE SAFE 1.5°C FUTURE

As described in Section 3.1, the 1.5°C Scenario requires an average annual investment of USD 4.4 trillion over the period 2021-2050. While the level of funding needed is large, it represents about 5% of the global 2019 GDP and is well within the current capacity of global financial markets, which reached around USD 200 trillion in 2019 (World Bank, 2019a; SIFMA, 2020). As well, global institutional investors alone manage about USD 100 trilion of assets but have so far largely remained on the sidelines of the energy transition (IRENA, 2020g). This pool of assets needs to be mobilised.

The rest of this chapter illustrates how the energy transition can be funded in terms of capital sources (public and private) and types of capital (equity and debt). The model used for this exercise is based on the energy industry's current funding structure, a deep understanding of financial markets, a set of assumptions about how financial actors perceive the risks and returns, the evolution of their beliefs over time, and their subsequent actions. This model represents one of many possible scenarios, but it is evident that **the financial capital needed for the energy transition is available and the required shift in investments is achievable.** Given a more proactive role of the public sector – one in which it establishes the right policy framework, emphasises and ensures long-term benefits from the energy transition, and supports and deploys innovative financing methods and instruments to lower the cost of financing – one may expect the speed of the transition and its associated costs to be even more beneficial.

The capital needed for the energy transition is available and the necessary shift in investments toward energy transition technologies is feasible.

3.2.1 Funding sources for the energy transition

To reach the investment levels required for the global energy transition, all sources of capital – private and public, equity and debt – will need to be mobilised. To date, most has come from private sources, a trend that is expected to intensify. Private sources include venture capital (typically investing in opportunities posing a higher risk and offering a commensurately high return) and industrial capital (project developers, corporations, and institutional investors). The latter are more likely to fund more established ventures. Public capital – from government entities (*e.g.*, sovereign states, municipalities, state-owned enterprises) and development finance institutions (DFIs) – will continue to play an important role in the energy transition. Public finance can be used to support relatively new solutions and markets, to fund enabling infrastructure, to reduce risks and financing costs to attract private investments, and to support the development of a pipeline of bankable projects. The measures that DFIs in particular can take to increase the effectiveness of investment are described in Box 3.1.

As transition technologies mature, the capital structure of projects tends to move from early-stage equity-dominant forms of financing towards low-cost, long-term debt to finance expansion, a trend that is expected to intensify in the climate-safe scenario. It is also worth noting that the global debt market is larger than the equity market: in addition to companies, governments, too, raise funding via debt issuances. The global debt market was estimated at USD 106 trillion in 2019, exceeding equity market assets estimated at USD 95 trillion (SIFMA, 2020). Debt can also be raised directly from commercial banks and institutional investors, either as corporate-balance-sheet lending or project finance. Debt from capital markets can take a variety of forms, but is most often structured as bonds.[1] In the recent past, new types of bonds whose proceeds fund green assets in particular have been issued with great success, indicating that a change in global lending practices is already under way. These are explored in Box 3.5.

1 Bonds are tradable, fixed-income instruments with a defined maturity. They represent a loan made by an investor to a borrower (typically corporations or governments).

BOX 3.1 De-risking investments in the energy transition

Policy makers and public capital providers (such as development finance institutions, DFIs) can help lower barriers to a greater scale up of investments in energy transition assets by taking actions to de-risk projects and mobilise private capital via blended-finance initiatives.

De-risking energy transition projects is imperative if long-term funding is to be made available at reasonable rates. High real or perceived risk is a frequent stumbling block for many energy transition projects, especially in emerging and developing markets. Risks that need to be allocated, mitigated or transferred include political risks in the host country (*e.g.*, war, expropriation), policy or regulatory risks (*e.g.*, changes in policies, introduction of new taxes), currency risks (*e.g.*, volatile exchange rate), counterparty risks (*e.g.*, default or non-payment by off-takers), grid and transmission risks, and liquidity risks. Risk-mitigation instruments such as guarantees, letters of comfort or intent, hedges against currency risks (*e.g.*, forward contracts and swaps[a]), letters of credit, and insurance products provide solutions for such risks but may not be easily accessible or affordable to market participants (IRENA, 2020h). Guarantees are the most effective leveraging instrument, being involved in 45% of all private capital mobilisation while representing only 5% of DFIs' commitments (OECD and Milken Institute, 2018). DFIs and other providers of public capital would do well to devote more of their efforts (and funding) to making such instruments widely accessible.

Table 3.1 summarises the types of risks encountered in many energy transition projects and the instruments available to public capital providers to address them.

Blended finance mechanisms such as co-financing (*e.g.*, public-private partnerships), on-lending, subordinated debt, and convertible grants and loans encourage the pooling of capital and the sharing of financial know-how, risks and returns among participating parties (IRENA, 2020g). Notably, the participation of DFIs through blended finance structures typically reduces the perceived risk of third-party investors and lowers the overall cost of capital (CFLI, 2019). Blended finance is therefore an essential leveraging tool that DFIs can deploy to magnify the effect of their funding and crowd-in private sources of capital. Greater use of co-financing to raise capital for green technologies and project finance[b] will encourage the sector's shift away from self-financing via balance sheets and towards greater access to global capital providers. Such mechanisms can also be coupled with risk-mitigation instruments provided by DFIs for an additional boost to risk-adjusted returns and bankability.

a. A forward contract is an agreement between two parties to buy or sell an asset at a pre-determined price at a future date. It is used to hedge against price fluctuations. A currency swap is a transaction in which two parties exchange an equivalent amount of money in different currencies at a certain date and agree to swap the same amount of money in the future at the original exchange rate or another pre-agreed rate.

b. Project finance is a fairly complex financing mechanism whereby, instead of the project cost being met by the project owners using their balance sheets, a separate legal entity is formed to own, manage and operate the project (*e.g.*, a power plant). Funding is typically provided by a group of financiers on a non-recourse basis in which case lenders have recourse only to the project's assets and not those of the sponsor. This structure is typically deployed for projects with a strong stand-alone business case (IRENA, 2020g).

TABLE 3.1 Key investment risks and financial risk-mitigation tools to address them

RISK	DEFINITION	RISK MITIGATION TOOLS
Political risk	Risks associated with political events that adversely impact the value of investment (*e.g.*, war, civil disturbance, currency inconvertibility, breach of contract, expropriation, non-honouring of government obligations).	Government guarantee, political risk insurance, partial risk/credit guarantee, export credit guarantee
Policy or regulatory risk	Risks associated with changes in legal or regulatory policies that have significant, adverse impacts on project development or implementation (*e.g.*, incentive programmes, taxes, interconnection regulations, permitting processes).	Government guarantee, potentially backed by partial risk/credit guarantee, export credit guarantee
Currency risk	Risks associated with changing or volatile foreign exchange rates that adversely impact the value of investments and arises when there is a mismatch between assets (revenues) and liabilities (debt financing).	Government guarantee, currency risk hedging (swap, forward), loans in local currency or covered in the power purchase agreement (PPA)
Counterparty (power off-taker risk)	Credit and default risk by a counter-party in a financial transaction. For renewable energy investments, it is related to the risk of default or non-payment by the power off-taker, typically the electric utility.	Government guarantee, political risk insurance, partial risk/credit guarantee, export credit guarantee, liquidity facility, put option/termination clause in the PPA
Grid and transmission risk	Risks associated with limitations in interconnection, grid management and transmission infrastructure (including curtailment risk).	Government guarantee, partial risk/credit guarantee
Resource risk	Risks associated with uncertainties around the availability, future price and/or supply of the renewable energy resource (*e.g.*, resource risks related to geothermal projects).	Government guarantee/grant/convertible grant, geothermal exploration insurance
Technology risk	Risks associated with use of nascent technology or unexperienced labour deploying it.	Specialised insurance products
Liquidity risk	Possibility of operational liquidity issues arising from revenue shortfalls or mismatches between the timing of cash receipts and payments.	Government guarantee, letter of credit, escrow account, liquidity guarantee, put option
Re-financing risk	Risk that a borrower is unable to re-finance the outstanding loan during the life of the project due to inadequate loan terms (high cost of borrowing, the maturity of the loan is mismatched with the lifetime of the asset).	Greater supply of capital market instruments used for re-financing (*e.g.*, green bonds/funds)
Natural disasters	Risk that a natural disaster will impact the ability of a counter-party to fulfil its obligations (*e.g.*, produce power, make payments).	Property and casualty insurance

Source: Adapted from IRENA (2016a).

Capital flows to areas of opportunity and higher risk-adjusted returns. As a new technology establishes itself, investors put capital into companies leading the deployment of the new technology, while pulling out of companies exploiting the old technology. This results in two feedback loops, further driving technological change and new capital flows. New technologies generally experience positive feedback loops. As capital flows into the new technology, the cost of capital falls, making it possible for companies to raise financing to expand production. As production expands and economies of scale are established, costs fall faster, and more capital is attracted into the new technology. At the same time, old technologies experience negative feedback loops. As investors lose faith in the old technology owing to its dimming prospects, capital exits rapidly, making it harder for incumbents to raise capital at affordable rates. The consequent reduction in production leads to higher unit costs, as total cost is spread over a smaller volume. This, in turn, forces incumbents to further curtail production, leading to lower investor confidence, write-downs, lower share prices and a reduced market share. Box 3.2 discusses how financing sources change at different stages of a technology revolution.

BOX 3.2 Funding sources at each stage of a technology revolution

Looking at the ongoing global energy transition as the current technology revolution can provide a good indication of how capital is likely to flow to new technologies over time and help policy makers choose the policies and enabling frameworks required to meet investors' needs at each stage of technology development, thus accelerating the energy transition.[a]

In the very early stages of a technology revolution – the so called gestation phase (up to a market share of approximately 1%) – various ideas and new technologies are tested. As private investors do not know which technology will succeed, innovation is most often done by entrepreneurs. The public sector is also an important source of financing at this stage, often funding demonstration projects or research and development.

When a winning technology begins to emerge, the revolution enters an irruption phase (or spring phase), where market share moves up to around 5%. This is the period when the new technology becomes cost competitive and starts to grow rapidly and attract considerable capital. In financial markets, the first movers will typically be venture capital and hedge funds that have a high tolerance for risk and are willing to invest in equity shares of small-scale businesses with high growth potential.

In the frenzy (or summer) phase, more and more investors allocate their capital to the new technology, and market share moves from 5% to around 25%. However, because capital moves faster than new options are created, this period tends to end in bubbles. As the new technology gains competitiveness, public sources of funding shrink as a share of total funding. Loans from commercial financial institutions are most prevalent as technology approaches competitiveness. However, commercial loans plateau and then begin to decrease once technology reaches competitiveness, as less costly ways to raise capital emerge. Industry equity grows, as the technology can now provide a viable business model. Corporations begin issuing bonds to raise capital earmarked for these technologies. Venture capital, on the other hand, may shrink in volume as the market becomes too competitive to yield the high margins they seek.

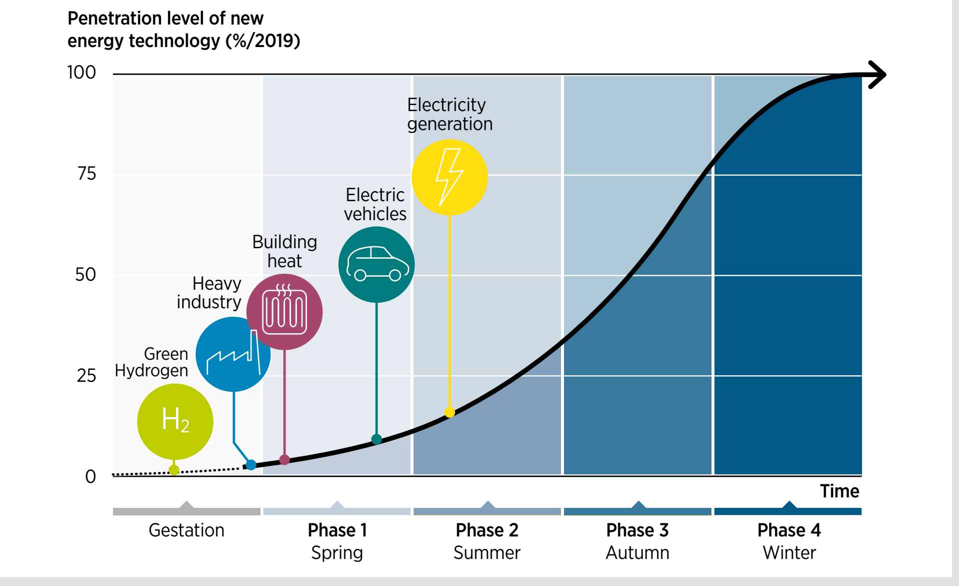
a. The five technology revolutions highlighted by Perez (2002) are the industrial revolution (after 1771); the age of steam and railways (after 1829); the age of steel, electricity and heavy engineering (from 1875); the age of oil, cars and mass production (after 1908); and the age of information and telecoms (after 1971).

At the end of the period of frenzy, an event occurs to trigger a collapse of the financial bubble. This is followed by a turning point, when regulatory changes are made to facilitate the further expansion of the new technology. This synergy (or autumn) phase marks the full flourishing of the technology, with market share moving from 25% to 75%. In this phase, investors understand the new technology and can make solid returns. As the technology begins replacing incumbents to become the dominant technology, the kickstarting role of public equity declines (though governments may choose for profit-making reasons to continue investing in the form of state ownership). At the same time, venture capital and loans from development finance institutions continue to decrease. In their place, industrial capital and financing raised through capital markets become the main funding sources for dominant technologies, with developers and corporations owning assets, and capital easily raised through bonds. Over time, however, bonds shrink slightly in volume as technology gains more dominance, and there is less need to go through capital markets.

Finally, in the mature (or winter) phase, the new technology progressively loses its competitiveness as a result of lower demand and higher costs. Capital then shifts away from such technology and onto the new promising opportunities.

In the context of the global energy transition, the electricity sector has been leading the change, followed by the transport sector (Figure 3.3). At the end of 2019, solar PV and wind represented 8% of global electricity generation (growing at 24% and 13% per annum, respectively). Both were in the frenzy phase of their development (IRENA, 2020i). Electric vehicles have recently irrupted; their market share in 2020 was 4% of sales. Other energy transition technologies (notably green hydrogen) are still in the gestation phase. Harder-to-abate sectors of the economy such as industry are in the same phase, where it is not yet clear which new carbon-free technology will be most successful. Each technology's stage of technical development and market penetration varies by country, depending on specific conditions.

FIGURE 3.3 Energy transition technologies and their development stage



3.2.2 Key changes in funding structures to 2050

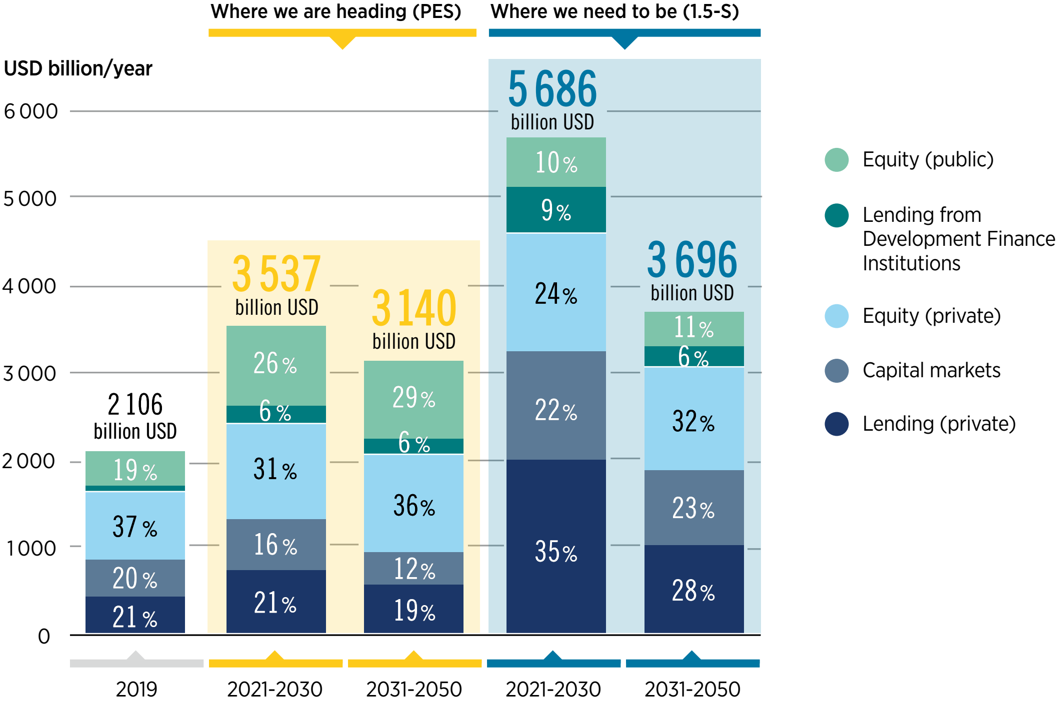
A climate-safe future as envisioned in the 1.5°C Scenario requires funding amounts, patterns of technological distribution and capital structures that are markedly different from those of the base year (2019) and the PES. Governments' ambitions and the speed of implementation of the required supportive measures will need to take hold decisively for the world to enact the 1.5°C Scenario.

In 2019, energy assets of all types were primarily financed by private sources, which contributed some USD 1.6 trillion, or about 80% of total investment in the energy sector. The majority of private funding came in the form of debt – either loans or bonds. The public sector, through DFI lending and public equity, provided about USD 450 billion. Broken down by technology, **most capital was invested in fossil fuel supply** (41%), followed by energy efficiency (22%), renewables (16%), power grids and other energy flexibility measures (13%), and power generation from nuclear and fossil fuels (8%). Investment in battery storage, hydrogen, and other technologies remained relatively small (BNEF, 2021a; IEA, 2020a; IRENA and CPI, 2020). On-balance-sheet financing by utilities, energy companies and developers accounted for two-thirds of the financing raised in 2019 for new construction of utility-scale renewable energy projects (estimated at about USD 150 billion). The other third came in the form of project finance structures (estimated at about USD 80 billion) (Frankfurt School-UNEP Centre and BNEF, 2020).

Figure 3.4 tracks sources of funding from 2019 to 2030 and 2050 under the PES and the 1.5°C Scenario. The public sources are public equity and loans from DFIs. The private sources are private equity, lending from capital markets, and lending from commercial banks and institutional investors.

In the 1.5°C Scenario, the increase in aggregate funding needed (an increase that will be driven largely by green technologies) would be covered by the private sector, as investors take decisive action to limit their exposure to assets not aligned with global climate actions and channel funds to green assets. Institutional investors, in particular, can contribute considerably to closing the financing gap for the energy transition (Box 3.3). **Public funding would continue to play a crucial role in lowering risks and barriers for private capital, supporting the policy environment, and enabling a just and inclusive energy transition** (as described in Chapter 4 and Chapter 5). While direct public funding in absolute numbers will grow through 2050, its share of total investments in the energy transition will decline over time as green technologies continue to attract a growing share of private capital.

FIGURE 3.4 Total average yearly investment by source and type of financing: 2019, PES and 1.5°C Scenario (2021-2030 and 2031-2050)



Sources: For 2019 investment: source and type of financing BNEF (2021a), IEA (2020a), IRENA and CPI (2020); for PES and 1.5°C Scenario: IRENA and BCG analysis.

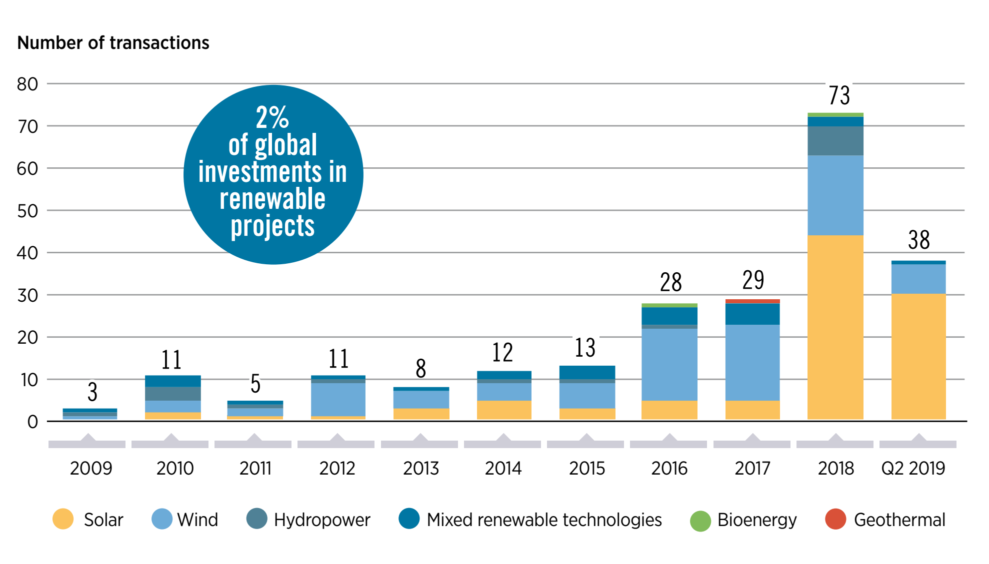
The additional capital needed for the 1.5°C Pathway would be largely covered by the private sector, while public resources would continue to be key to lower the risk perception for investors.

BOX 3.3 Institutional investors and the energy transition

Institutional investors represent one of the largest capital pools in the world, yet their potential role in financing the energy transition has so far remained largely untapped. This will have to change if the 1.5°C Scenario is to be realised.

IRENA investigated the investment behaviour of institutional investors in the renewable energy sector by analysing a sample of 5 800 pension plans, insurance companies, sovereign wealth funds, and endowments and foundations. By 2018-2019, this core group of institutional investors managed about USD 87 trillion in assets, yet IRENA's analysis shows that while their participation in renewable energy transactions has increased in frequency over the past two decades, it remains subdued (IRENA, 2020g). By 2018, a fifth of such investors had invested in renewable energy funds, representing about USD 6 billion per year, whereas only 1% of such investors had invested directly in renewable energy projects. While the number of direct investments in renewables has grown over time, institutional investors still provided, on average, only 2% of total renewable energy financing in 2018 (Figure 3.5) (IRENA and CPI, 2020).

FIGURE 3.5 Number of renewable energy project transactions involving institutional investors, by technology, 2009 – Q2 2019



Source: IRENA analysis based on Preqin data (2019).

Note: "Mixed renewable technologies" include more than one type of renewable energy technologies.

Renewable energy represents only one of the energy transition solutions needed to achieve the 1.5°C Scenario. Institutional capital has the potential to bridge the investment gap in other areas of the energy sector as well. But to activate this important capital pool, a range of co-ordinated actions involving regulations, policy levers, capital market solutions and internal changes will be required. These include:

- **Internal capacity building** on the part of institutional investors will be needed in some markets to enhance skills in the financial, technical and legal structuring of energy transition deals. In addition, investors also need to hone their skills in climate risk and energy sector analysis and governance. The required skills transfers can be advanced by collaborating with other institutional investors and development finance institutions to co-finance trades, and by participating in institutional investors' groups.
- **Project pipelines** must be built to make energy transition projects more bankable and to increase their ticket size– both aimed at making them more attractive to institutional investors. Solutions include greater provision of risk-mitigation instruments by public financiers, standardisation of contractual agreements, aggregation of projects into larger transaction blocks, and a wider deployment of blended finance initiatives between public capital providers and institutional investors.
- **Capital market solutions** can help channel institutional capital into energy transition technologies by enlarging the supply of green investment vehicles, created in accordance with a green taxonomy aligned with global climate targets (Box 3.4). Such vehicles include project bonds, project funds and green bonds; all can provide institutional investors with a desirable scale, credit assurance (when rated) and liquidity (when listed on an exchange).
- **Policy and regulatory actions** can be a powerful lever to steer institutional capital towards green assets. In addition to policies that help promote overall renewable energy deployment, these include 1) review and revision of investment restrictions that may limit institutional investors' investments in real assets like renewable projects; 2) adoption and development of sustainable finance principles, including frameworks for calculation and disclosure of climate-related risks; and 3) application of long-term sustainability mandates and green investment targets.

There are already signals in the market that institutional investors are re-evaluating their portfolios and shifting their attention to sustainable assets, including renewables. Many institutional investors – including Norway's Government Pension Plan Global, Sweden's Första AP-fonden, the United Kingdom's National Employment Savings Trust, and Dutch Robeco – have announced their intention to divest from fossil fuel assets to reduce their exposure to sustainability-related risks (Ambrose 2019; IEEFA, 2020a; IEEFA, 2020b; Tuck, 2020). Others have begun to make net zero emissions pledges. These include the Ontario Teacher's Pension Plan, the New York State Common Retirement Fund, and a number of major British pension plans, to name a few (Ceres, 2020; Jolly, 2021; OTPP, 2021).

Keeping the world on a climate-safe pathway will hinge on the participation of institutional investors in the energy transition. The pace of the shift of institutional capital from fossil fuel assets to green energy technologies, however, needs to quicken.

In the 1.5°C Scenario, governments increase both their ambitions and their speed of implementation. While still providing a sizable amount of funding to finance energy assets (their financing in absolute terms increases from USD 460 billion in 2019 to USD 1.1 trillion in the next decade and USD 630 billion in 2031-2050), direct public sector funding into the technological avenues of the transition decreases over time from 22% of total spending in 2019 to 19% in the period 2021-2030 and 17% in the following decades. In the meantime, considerable public funding will be needed for supportive policy measures and to create an enabling environment (Chapter 4). Private lenders, sitting on plenty of capital, are increasingly aligned with climate targets and more reluctant to provide loans to fossil fuels. They are expected to phase out fossil fuel investments relatively quickly. Governments, too, are focusing on supporting transition-related technologies and will play a key role in areas related to supportive policies, stricter regulation, targeted financial support for new technologies, and infrastructure.

In the PES, there is an asymmetry of beliefs, whereby the private sector moves faster than the public sector to exit brown technologies. In the 1.5°C Scenario, this asymmetry remains in some countries; however, only a relatively minor shift occurs in the shares of private and public equity investment in these technologies. Moreover, in the 1.5°C Scenario, this partial asymmetry would be resolved in the period 2021-2030 as public and private stakeholders unite in taking equally decisive action to shift assets towards technologies aligned with climate targets and actions. The share of public investments (debt and equity) in fossil fuel supply, for example, drops from 51% in 2019 to 15% in the 2031-2050 period in the 1.5°C Scenario as public investment in brown technologies falls. This analysis is based on the perception that regulators around the world will put growing pressure on financial actors to align their assets with climate targets. Box 3.4 provides an overview of recent developments in the green taxonomy and climate-related risk disclosures that will help drive the investment shift.

In absolute terms, as noted, the public sector is still projected to invest in the energy sector significantly more on average annually over the 30 years from 2021 to 2050 (USD 779 billion) than it did in 2019 (USD 461 billion). An increase in public debt financing – from 7% in 2019 to 14% in 2021-2030 and 11% in the following two decades – will be an important facilitator for other lenders, especially in developing markets. In energy efficiency for buildings, particularly, public debt plays an important role (it is expected to make up 20% of the overall funding need for the sector in 2021-2050), given that the business case for these measures remains difficult and requires government mandates and public financing.

In 2021-2030, DFI lending is projected to grow from around USD 60 billion in 2019 to over USD 550 billion per year under the 1.5°C Scenario – compared with USD 200 billion in PES – before declining in the period between 2031 and 2050. The initial growth over the 2019 level represents about 55% of the balance sheet of multilateral and regional DFIs, but this may be achievable, since DFIs have a lending curve similar to governments and can increase their lending portfolio more easily than commercial banks. Hence, while such investments are challenging, they should also be feasible. In addition to direct lending, DFIs should boost the effectiveness of their interventions by focusing on activities that mobilise private sources of funding, such as blended finance transactions (including co-financing with private investors) and risk-mitigation instruments to make energy transactions more bankable for private investors (see Box 3.1).

In the 1.5°C Pathway, private sector rapidly redirects its capital towards transition technologies, while governments speed up implementation of supportive policies.

BOX 3.4 Green taxonomy and climate-related risk disclosure

Policy makers can help channel global capital towards sustainable assets by adopting green taxonomies aligned with climate targets and by requiring investors to disclose and reduce their climate-related risks. Significant developments on both fronts are already underway but need to be further strengthened and globally deployed.

The **green taxonomy** is the cornerstone of the sustainable finance movements that are spreading rapidly in global capital markets. As investors increasingly seek green assets, and as financial markets in turn offer more green securities, the question arises as to what assets are to be considered green – with the risk of "greenwashing" looming large. To date, many different definitions of green and sustainable have been used in the financial markets, with varying levels of alignment with science-based climate targets. This is why the market has so eagerly awaited the European Union's Sustainable Finance Taxonomy, released in April 2021. The EU taxonomy defines what constitutes sustainable activities and also requires providers of sustainable investment products in the Union to disclose how aligned they are with the taxonomy (European Commission, 2021a). Other states and regions are expected to take similar action, making it easier for the growing pool of investors seeking sustainable assets to identify qualifying opportunities. China, for example, has already announced changes in its green taxonomy that bring it closer to the EU standard (Li and Yu, 2021).

Climate-related risk disclosure is another recent development in the capital markets with potentially important effects on global investments. It would help move climate risk out of the "non-traditional" financial risk category and well into the spotlight of global investors. Market participants are already making significant inroads in this domain. These include organisations that develop climate-risk calculation and reporting standards, such as the Task Force on Climate-Related Financial Disclosures (TCFD); organisations that help align climate-risk disclosure with global accounting standards, such as the Sustainability Accounting Standards Board and the Climate Disclosure Standards Board; and a host of sustainable finance initiatives that promote stakeholder co-operation and adoption of such standards. Table 3.2 for example, presents TCFD's recommendations regarding "decision-useful" climate-related disclosure.

In the end, it will be up to regulators to mandate climate-risk reporting and enforce such mandates. Several countries are already taking such measures. The French Energy Transition Law, adopted in 2015, requires French institutional investors (including asset managers and banks) to disclose their greenhouse gas emissions and how climate risks will affect their assets (Mazzacurati, 2017). More stringently, the British government announced that it would require all listed companies and large asset owners to disclose climate-related information in line with TCFD recommendations by 2022 (Government of the United Kingdom, 2019). Furthermore, in April 2021, New Zealand introduced legislation to require banks, insurers and investment managers to report their climate-related risks and how such risks will be managed. If adopted, New Zealand's measure would be a world first (Reuters, 2021).

TABLE 3.2 TCFD recommendations regarding 'decision-useful' climate-related disclosure

GOVERNANCE	STRATEGY	RISK MANAGEMENT	METRICS AND TARGETS
Disclose the organisation's governance around climate-related risks and opportunities	Disclose the actual and potential impacts of climate-related risks and opportunities on the organisation's businesses, strategy, and financial planning where such information is material	Disclose how the organisation identifies, assesses, and manages climate-related risks	Disclose the metrics and targets used to assess and manage relevant climate-related risks and opportunities where such information is material
a) Describe the board's oversight of climate-related risks and opportunities	a) Describe the climate-related risks and opportunities the organisation has identified over the short, medium, and long term	a) Describe the organisation's processes for identifying and assessing climate-related risks	a) Disclose the metrics used by the organisation to assess climate-related risks and opportunities in line with its strategy and risk management process
b) Describe management's role in assessing and managing climate-related risks and opportunities	b) Describe the impact of climate-related risks and opportunities on the organisation's businesses, strategy, and financial planning	b) Describe the organisation's processes for managing climaterelated risks	b) Disclose Scope 1, Scope 2, and, if appropriate, Scope 3 greenhouse gas (GHG) emissions, and the related risks
	c) Describe the resilience of the organisation's strategy, taking into consideration different climate-related scenarios, including a 2°C or lower scenario	c) Describe how processes for identifying, assessing, and managing climate-related risks are integrated into the organisation's overall risk management	c) Describe the targets used by the organisation to manage climate-related risks and opportunities and performance against targets

Source: TCFD (2019).

Far more debt is incurred to fund energy assets (particularly green assets) in the 1.5°C Scenario than in the PES, as greener assets are better able to attract low-cost long-term financing. Over time, brown technologies have growing difficulty finding debt financing at affordable costs and must rely on equity financing.

In the 1.5°C Scenario, debt would meet most of the increase in the funding needs driven by green technologies. Debt's share in the finance mix grows from 44% in 2019 to 66% in 2021-2030 and 57% in 2031-2050 (compared with 43% and 39%, respectively, in the PES). In absolute terms too, debt issuances grow, experiencing a fourfold increase – from USD 932 billion in 2019 to an average USD 3.7 trillion per year in 2021-2030, before declining to USD 2.2 trillion per year in the following two decades. Technologies aligned with climate targets should have no difficulties in attracting long-term debt financing under satisfactory terms, including in capital markets. Box 3.5 presents an overview of the green bonds market and the trend of record issuances since 2014, highlighting the massive potential for further growth in green debt. The shift toward higher shares of debt capital in the 1.5°C Scenario reflects a reduction in the perceived risk of energy transition technologies.

Going forward, long-term climate commitments and growing pressure on financial institutions to align their investment portfolios with the targets of the Paris Agreement are likely to make it increasingly difficult for brown technologies to obtain commercial loans at reasonable rates. As many lenders would be increasingly reluctant to back massive investments in fossil fuel assets, these technologies would need to meet their funding needs by retaining earnings (less dividends) and potentially issuing new stock. In the PES, where 44% of energy sector investments would still be directed to fossil fuel and nuclear assets, the share of equity would grow from 56% in 2019 to 57% up to 2030 and 64% in the period 2031-2050. Under the PES, equity would fund about 70% of the additional investments in fossil fuel technologies (or USD 814 billion per year), the majority of which (61%) would come from the public sector.

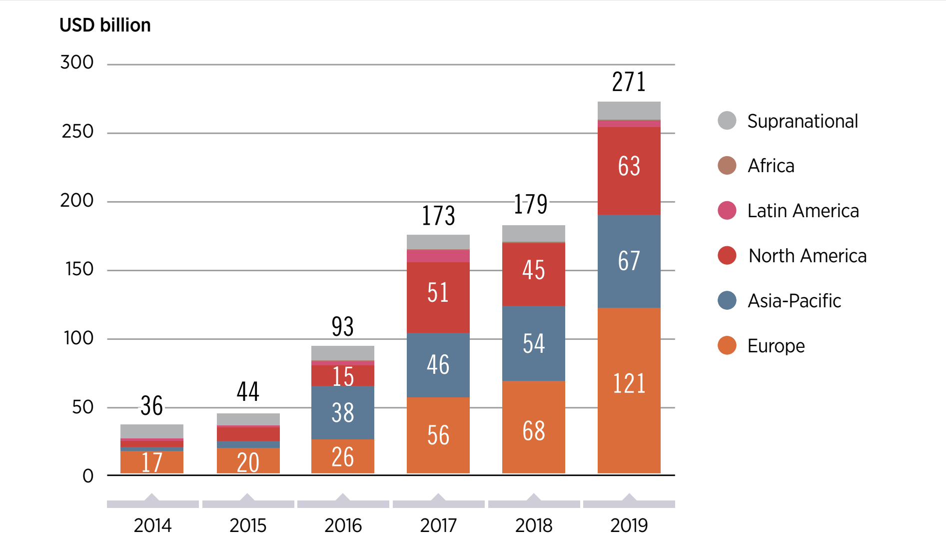
BOX 3.5 Green bonds

The rise of green bond issuances in the recent past indicates that a shift in lending behaviour is already under way, as assets aligned with climate targets are attracting growing amounts of financial capital, especially long-term debt. However, the potential for further growth remains enormous and can benefit from active support from governments and market participants to help make the 1.5°C Scenario a reality.

Green bonds help issuers (governments, corporations) attract investors that have sustainability goals, providing them with greater transparency over the use of proceeds than is typically the case with traditional bonds. Green bond proceeds fund green projects in renewable energy, energy efficiency, green buildings, clean transport, sustainable water management, waste and pollution control, and nature-based assets, among others (CBI, 2019). Most green bonds fund multiple green categories. IRENA's analysis of more than 4 300 green bonds issued over the past decade shows that about 50% (by volume, in USD) included renewable energy, while 16% were earmarked solely for renewable assets (IRENA, 2020j).

The green bond market started about a decade ago with initial issuances from development finance institutions such as the European Investment Bank in 2007 (for EUR 600 million) and the World Bank in 2008 (EIB, 2017; World Bank, 2019b). Since then the market has diversified away from DFIs to a variety of issuers including local, state and federal governments, and a variety of issuing companies (financial institutions, corporations). The green bond market has also grown rapidly, attracting about USD 271 billion in issuances in 2019 (Figure 3.6) (IRENA, 2020j). Further, in 2020, despite the COVID-19 pandemic, the market recorded record-high issuance of around USD 290 billion and reached the USD 1 trillion mark in cumulative issuances (CBI, 2020). However, given that the global bond market as a whole is worth about USD 100 trillion, the potential for further growth in the green bond market remains very large.

FIGURE 3.6 Annual global green bond issuance by region, 2014-2019



Source: IRENA, 2020g; based on data from the Environmental Finance (2020).

To realise this potential, several market barriers need to be lowered. These include lack of awareness of the benefits of green bonds (and hence lack of investor demand); lack of regulatory clarity and mandates surrounding the green taxonomy and green certification, bond issuance and reporting on use of proceeds; and relatively high transaction costs. To lower these barriers, regulators can adopt issuance and certification standards aligned with climate targets such as those offered by the Climate Bonds Initiative. They can also provide economic incentives in co-operation with DFIs to fund demonstration issuances and offer grants to offset transaction costs. Policy makers can co-operate with green bond leaders in the financial industry to build financial skills needed to issue green bonds and other new instruments. Finally, policy makers can create green mandates for crucially important capital holders such as institutional investors, thereby ensuring steady demand for green financial instruments (IRENA, 2020j).

3.3 THE IMPACT OF THE ENERGY TRANSITION ON FINANCING RISKS AND CAPITAL POOLS

While adequate funding for the energy transition is achievable, capital availability will depend largely on investors' assessment of risks and returns. Several trends are likely to influence this perception – positively or negatively. Dedicated policies and capital market interventions may be needed to mitigate risks in some contexts so as to increase the availability of affordable capital and increase the speed of the transition.

Observed trends related to the inherent nature of energy transition technologies include the broadening geographical distribution of investments (with more assets being built in developing countries); the shift in financing structures from operations-intensive to capital-intensive expenditures (resulting in a frontloading of investments); and fragmentation of markets and proliferation of smaller projects (reducing transaction size for investors); and the introduction of new technologies. Some of these trends may have a positive or mixed effect on capital pools. Others will need to be managed via dedicated policies and capital market interventions to mitigate risks and increase the availability of affordable capital.

Other trends in the enabling environment include those related to the shift of power systems towards liberalised markets in some countries and the adoption of policies to keep the world on a climate-safe pathway; the forced retirement of fossil fuel assets to accelerate the transition; the wider adoption of policies that eliminate distortions and incentivise energy transition solutions; larger public investments in supportive infrastructure; increased awareness among consumers and citizens about the potential and benefits of transition-related solutions; and support for innovation and the development of domestic value chains.

3.3.1 Observed trends related to the nature of the energy transition and their impact on investment risks

The broader geographical distribution of investments. As the global transition unfolds, the geographical distribution of investments in energy assets is broadening. With an increasing number of investments located in countries characterised by challenging political, technological and market conditions, investors' overall perception of risks is expected to increase. Public finance can be particularly effective in supporting technologies and regions that private investors perceive as too risky. This can be done through blended finance and risk mitigation (Box 3.1). In addition, activating different types of investors with varying requirements in terms of size, location and risk–return profile could help attenuate the increased perception of risks related to this trend. Creating investment vehicles that open access to green projects in different countries can also help investors access new opportunities abroad.

The shift from operations-intensive technologies to capital-intensive technologies. The energy transition will entail a shift from financing fossil fuel technologies, which rely heavily on operating expenditures (OPEX), to energy transition technologies, which generally have a more capital-intensive profile (CAPEX). Depending on context, this trend affects the funding structure differently with respect to preexisting perceived risks. A rise in CAPEX makes an investment more sensitive to the reward that investors and lenders expect, which depends largely on the perceived risk of the investment. Risk perception would thus have a much greater effect on the viability of the investment. Therefore, it is easier for a CAPEX-intensive investment (*e.g.*, solar and wind) to compete with an OPEX-intensive investment (*e.g.*, fossil fuels) in a low-risk environment than in a high-risk environment. This explains why renewable energy projects have a much harder time reaching financial closure in developing countries. There is also a temporal difference. The viability of a CAPEX-intensive investment will depend on perceived risks over a short period - essentially around the time of the financial closure, when interest rates and the financial model that predicts a certain return on investment crystallise, on trade agreements, power systems structures, and contractual clauses, among other factors. An investment in OPEX-heavy technologies or assets by contrast, will be affected over its lifetime by fluctuations in the cost of the resource (coal, fuel or gas). DFIs can play a key role in this context, by facilitating access to risk-mitigation instruments needed to lower early-stage risks, both real and perceived.

Several observed trends related to the energy transition are likely to affect investors' risk perception and the availability and cost of capital for energy-transition technologies.

More fragmented markets and smaller projects. Several energy transition technologies (notably rooftop solar PV and other individually adopted technologies) are distributed, which affects their risk profile in a number of ways. On the one hand, some decentralised installations such as heat pumps are only marginally affected by political risk, if at all, as the bulk of the support they receive is typically provided during their installation. Moreover, counterparty risk is also generally reduced as the investor and the off-taker are often the same entity, and revenues come mostly in the form of reduced electricity costs (for power assets) or overall energy expenses (for energy efficiency projects). However, the smaller ticket sizes of decentralised projects may reduce their attractiveness in the eyes of traditional financiers (*e.g.*, commercial banks) owing to the higher transaction costs involved and the inability of some installers to provide guarantees to back their loans. In these instances, contract standardisation and bundling of projects through securitisation can help to reduce transaction costs by increasing the overall ticket size (IRENA, 2020g; IRENA and CPI, 2020). Targeted regulations and public capital support are fundamental to help such projects become more widespread and gain commercial momentum.

Innovation and introduction of new technologies. While some renewable energy technologies such as solar PV and onshore wind have been widely deployed worldwide and are now relatively mature, other technologies, such as green hydrogen, are still at early stages of development and adoption. Those solutions still represent comparatively high-risk investments owing to uncertainties related to the technology itself as well as the ecosystem supporting it. For instance, the supporting infrastructure (*e.g.*, distribution networks) may not be fully developed by the time green hydrogen is ready to be deployed, and available support schemes may be unsuitable or adjusting too slowly to the pace of innovation. While these conditions are attractive for some investors looking for higher returns from riskier investments (such as venture capital providers, for example), traditional investors may be reluctant to commit to these technologies and may want to wait until they reach a certain level of maturity. Public sector financing may therefore be needed to provide the initial investment injection.

3.3.2 Observed trends in power system structures and enabling environments and their impact on investment risks

Power structures transitioning to more liberalised systems. For power structures moving towards more liberalised systems, power generation is remunerated in the wholesale market based on clearing prices, which are typically determined according to the marginal cost of the most expensive active generator in a certain time slot. As the share of renewables increases in the system, this structure increases investors' exposure to price and off-take risks, thus increasing their reluctance to invest in variable renewable energy. Price risks arise from market price variations reflecting the fundamental demand-supply balance and the clearing price, which declines with rising penetration of low-marginal-cost renewable energy. Price risks can be mitigated through long-term off-take agreements. But such agreements sometimes come with counterparty risks, including the risk of payment delays, as the off-taker may not always be creditworthy. Because merchant markets risk limiting the penetration of variable renewable energy into the power system, it remains unclear whether this trend will continue in the future. A restructuring of power markets or a separation of generation risks and balancing risks through new auction structures will be needed to ensure higher penetration of renewables in the market (IRENA, 2020d) (see In Focus section in Chapter 4).

Increased implementation of policies to accelerate the retirement of fossil fuel assets To accelerate the energy transition and achieve decarbonisation targets by 2050, many existing carbon-intensive industries and assets will face early retirement and become stranded.[2] Implementing policies to retire fossil fuel assets would give a strong signal to investors about governments' commitment to the energy transition and would reduce risks related to the political environment and the stability of transition-related plans. However, the way early retirement is managed and compensated by governments could negatively affect the risk perception of energy sector investors. Abrupt change, in particular, before financial players have not had a chance to adjust their positions, could potentially have negative ripple effects in the overall financial market and the economy, given that a large share of pension funds' assets, for example, are currently invested in fossil fuels. To reduce uncertainties and risks for energy sector investors, the phase-out of fossil fuel assets should be carried out with transparent and strategic planning, a clear timeline, and clear guidelines and mandates for investors to redirect their assets towards industries aligned with climate targets. Governments could compensate for some of the losses incurred when these changes result in excessive social harm – for example, by developing programs for retraining and relocation of the workforce. This approach may be less disruptive and contribute to the promotion of a just transition (see Section 5.3).

2 Stranded assets are defined as the remaining book value of assets substituted before the end of their anticipated technical lifetime to achieve 2050 decarbonisation targets, without recovery of any remaining value (IRENA, 2017b).

Wider adoption of policies that eliminate market distortions and incentivise energy transition solutions. While many renewable energy technologies have achieved competitive cost structures, some transition technologies such as electric vehicles and heat pumps have not yet reached that point against fossil fuel alternatives in many contexts. As governments remove existing support schemes for fossil fuels (Congressional Research Service, 2019) and introduce fiscal policies such as carbon pricing (OECD, 2016), the ability of green solutions to compete against traditional solutions is enhanced. While the impacts on investment risks will ultimately depend on the effectiveness, stability and long-term continuity of such policies, recent pledges of carbon neutrality and other ambitious climate goals made by governments around the world (see Chapter 4) suggest that the risk of unfavourable retroactive policies is relatively low.

Increased public investments in supporting infrastructure. Supporting infrastructure, such as grid enhancements and charging stations for electric vehicle, are a key enabler of the energy transition. Public commitments to enabling infrastructure have a knock-on effect on investment, since having the necessary infrastructure in place, coupled with supportive policies, can make it possible for new technological solutions to scale up, thus boosting investors' confidence in the viability of energy transition technologies. In addition, public participation in the provision of infrastructure can improve credit quality and the certainty of operational revenues, lowering investors' risks along this dimension.

Increased consumer awareness of the benefits and reliability of energy transition solutions. Energy users, from corporations to households, are increasingly demanding cleaner and more efficient solutions for their energy needs. In some cases energy users have become "prosumers", producing energy through rooftop solar PV in combination with energy-storage technologies and electric vehicles. In 2020, for example, non-energy corporations purchased a record-high level of clean energy through corporate power purchase agreements (BNEF, 2021b). By creating demand for energy transition technologies, this shift in consumer preferences will reduce investors' risk perception and push them to seek more such investment opportunities.

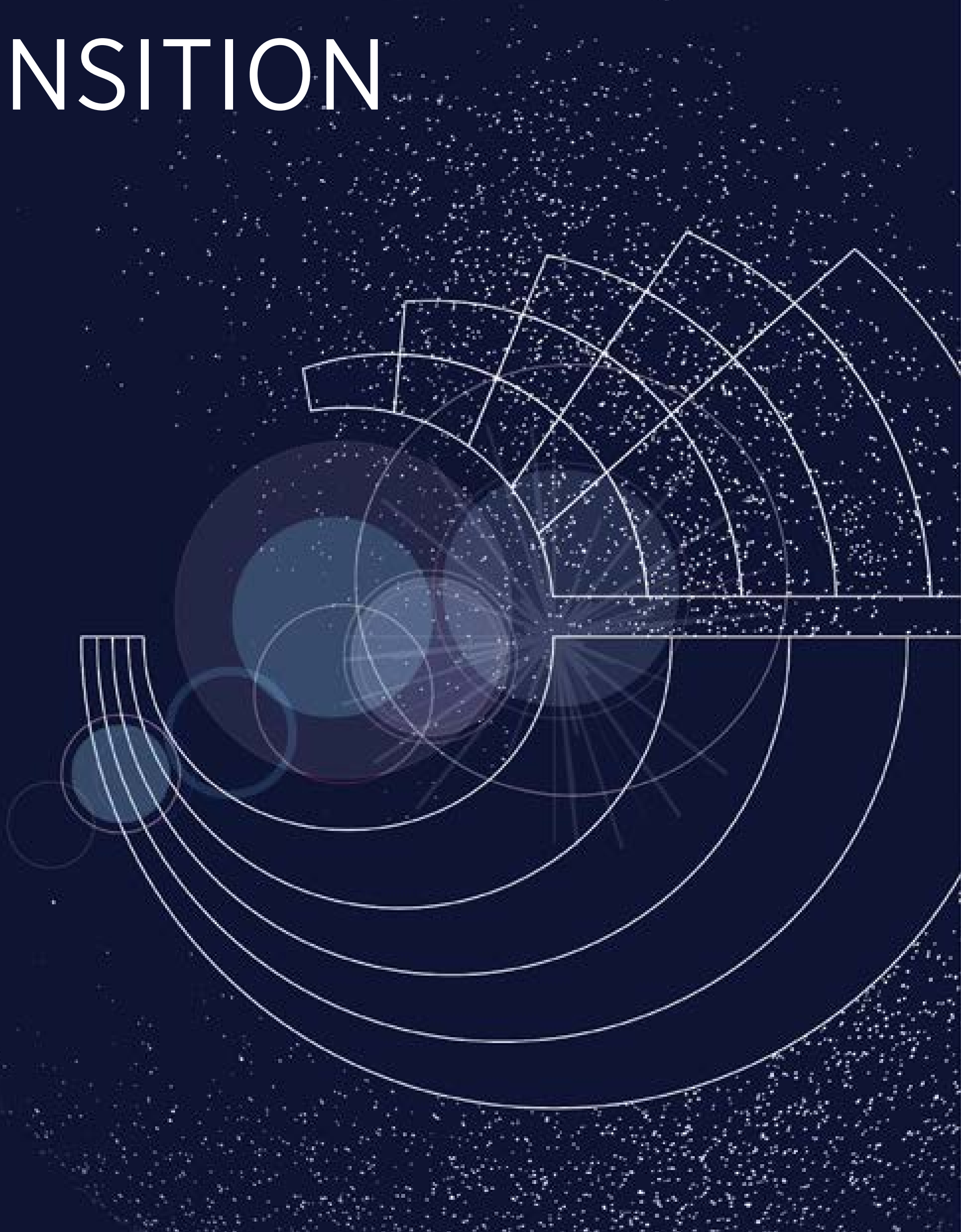
Increased adoption of policies and measures to support the development of domestic value chains. The energy transition brings immense opportunity for the development of local supply chains, creating value and jobs locally (Chapter 5). As more countries plan to seize this opportunity, especially in the process of recovery from the COVID-19 crisis, more governments are weighing support for the development of domestic supply chains. For renewable energy power plants, this is often done through various policy mechanisms, such as mandating a minimum level of local content in supply chains (*e.g.*, as a prerequisite for accessing financing, qualifying for a feed-in tariff or participating in an auction), or incorporating them as evaluation criteria (*e.g.*, in an auction). Instruments for the development of domestic value chains can lower risks related to supply chains, which became evident during the COVID-19 crisis. However, localising supply chains may imply higher costs for investors in the short term if the technology employed is not the lowest-cost option available, and if local capabilities are not readily available.

3.4 CONCLUSION

As renewables' costs continue to fall, fossil fuel supply and fossil and nuclear power generation technologies are abruptly losing their cost-competitiveness. Due to their superior risk-adjusted returns, investments in renewables are increasingly outstripping those of brown technologies. In 2019, global investments in new renewable power exceeded investment in new fossil fuel power by more than three times (Frankfurt School-UNEP Centre and BNEF, 2020). In 2020, in the midst of the COVID-19 pandemic, the competitiveness of fossil fuel assets was further jeopardised as their returns became uncertain and governments around the world announced ambitious climate commitments and green recovery plans (IRENA, 2020b) (see Chapter 4). As these technologies are gradually identified for phase-outs, investors' appetite for them will drop, the cost of financing will increase, and private capital will move increasingly to new energy technologies. A larger share of private capital can be expected to flow towards energy transition technologies as the pressure to advance the transition grows. Capital markets and institutional capital can be expected to play an increasing role over the coming years as green technologies gain even more market share and provide stable returns.

Although the energy transition is gaining momentum, the immediate nature of the climate emergency and the global Sustainable Development Goals require a much faster pace of change. Markets alone are not likely to move quickly enough to take transition technologies up the development curve at the speed needed. Therefore, policy makers and public finance institutions remain key in ensuring that the energy transition occurs in time and with optimal socio-economic effects. The next chapter describes in detail a comprehensive set of policy measures that governments can use to support the energy transition.

04 COMPREHENSIVE **POLICY FRAMEWORK** FOR THE ENERGY TRANSITION



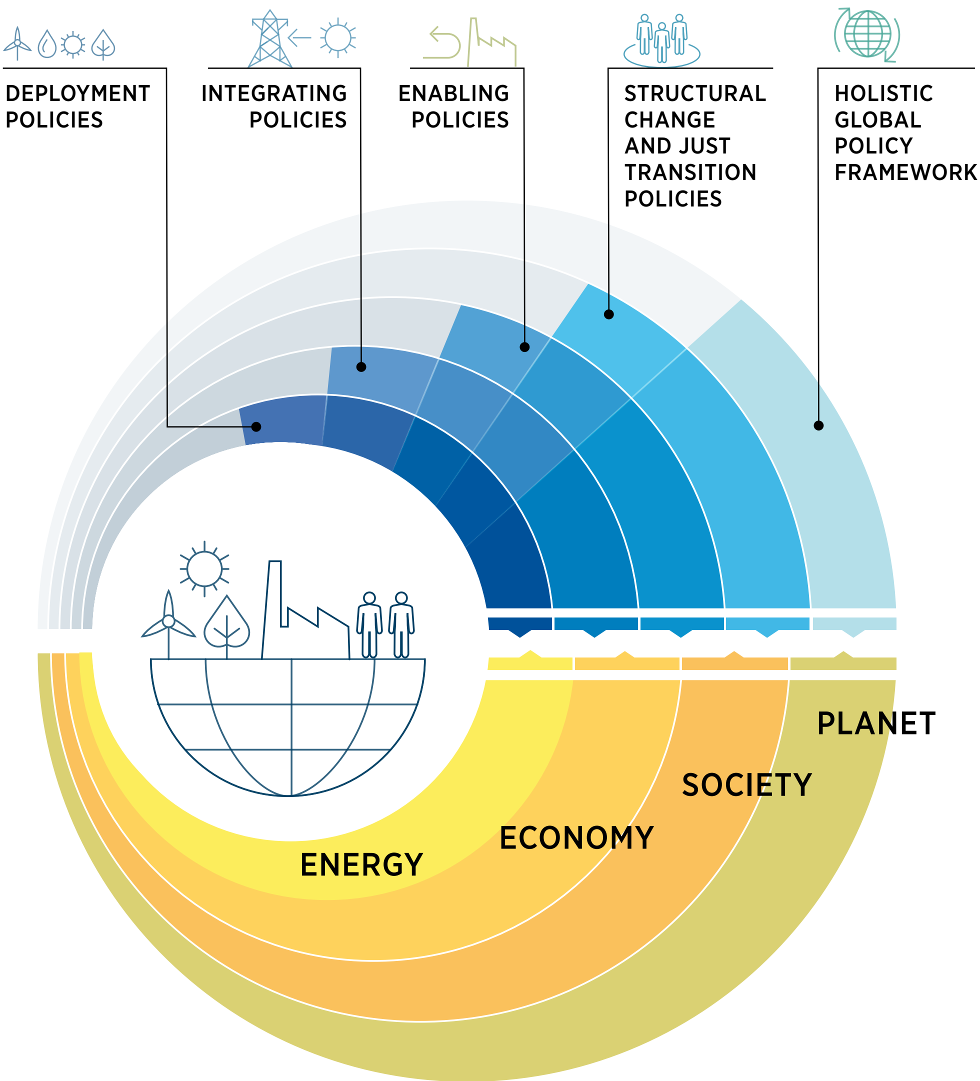
Governments have a crucial role to play in advancing a just energy transition and placing the world on a trajectory toward limiting the global temperature rise to 1.5°C. The surrounding discourse often defines governments' main responsibility as creating an enabling environment for private investments through predictable and stable policies and de-risking public financing tools. In fact, a much broader set of policy measures is required to facilitate the adoption of the entire spectrum of energy transition solutions needed to avoid a rise over 1.5°C and align short-term actions with longer-term climate and socio-economic development objectives.

This chapter discusses the components of a comprehensive policy framework necessary to advance an energy transition aligned with the 1.5°C Pathway, and focusing on accelerating the adoption of technology solutions and ensuring a just and inclusive transition which maximises socio-economic benefits for all. The broad policy framework for a just energy transition and its interaction with the main system layers of energy, society, economy and planet is shown in Figure 4.1.

A host of **cross-cutting enabling policies**, often involving institutions outside the energy sector, contribute to a conducive environment for the energy transition covering all its technological avenues. These include policies that set ambitions and issue clear signals to stakeholders, eliminate distortions, incentivise the uptake of solutions and facilitate access to affordable financing, among others. These policies are described in Section 4.1. **Deployment policies to support all the essential technological avenues of the energy transition** – namely, renewable energy for power and end uses (heating and cooling and transport), energy efficiency, electrification, sustainable bioenergy and green hydrogen – play a fundamental role in accelerating the adoption of related technologies. Such policies support market creation, thus facilitating deployment, reducing technology costs and increasing adoption at levels aligned with energy transition needs. They are described in Section 4.2, along with some of the **integrating policies** enable the integration of energy transition related technologies into the energy system, the economy, society and planet.

It is essential to recognise that regions and countries face markedly different contexts with varied starting points, socio-economic development priorities and resources. Regardless of starting point or context, however, any structural change in an economy (including an energy transition) will bring benefits, as well as challenges in the form of misalignments that may become evident in finance, labour markets, power systems and the energy sector itself. These misalignments, if not well managed, risk inequitable outcomes and a slower pace of the energy transition. Therefore, a set of **structural and just transition policies**, along with the creation of strong institutions to ensure policy co-ordination and cohesion, is required to manage potential misalignments. They are discussed in Section 4.3.

FIGURE 4.1 Enabling policy framework for a just and inclusive energy transition



DEPLOYMENT POLICIES

For example:

Renewable energy targets

Regulatory and pricing policies (e.g. feed-in tariffs and auctions)

Mandates and planned replacement

Tradable certificates

Fiscal and financial incentives

INTEGRATING POLICIES

For example:

Measures to enhance system flexibility

Policies for the integration of off-grid systems with main grid

Policies for sector coupling, including infrastructure

Alignment of energy efficiency and renewable energy policies

ENABLING POLICIES

For example:

Ambitious energy plans

Policies to level the playing field (e.g. fossil fuel reforms)

Policies to ensure the reliability of technology (e.g. quality and technical standards, certificates)

RD&D and innovation policies

STRUCTURAL CHANGE AND JUST AND INCLUSIVE TRANSITION POLICIES

For example:

Measures to adapt socio-economic structure to the energy transition

Labour market policies and social protection (e.g training and retraining)

Industrial policy

Trade policies (e.g. trade agreements)

Environmental and climate policies

HOLISTIC GLOBAL POLICY FRAMEWORK

For example:

Public investment for structural transition elements

International climate finance based on equity and fairness

Carbon pricing aligned with climate goals

Progressive government revenue recycling to address inequalities

A broad set of policy measures is required to facilitate the adoption of energy transition solutions needed to align short-term actions with longer-term climate and socio-economic development objectives.

The policies needed to advance the energy transition reinforce one another and have implications for the energy system, economy, society and planet. An integrated policy approach is necessary to account for feedback among policies and across systems to ensure a timely, just and inclusive energy transition.

A **holistic global policy framework** would bring countries together to commit to a just transition that leaves no one behind and strengthens the international flow of finance, capacity and technologies in an equitable manner. Climate policies represent a crucial piece of such a framework. A portfolio of relevant measures would include fiscal policies such as adequate carbon pricing covering emissions across sectors and meeting public funding needs for the implementation of policies to foster deployment and enabling conditions, and to address structural and just transition aspects including industry creation, education and training, and social protection. The needed financial resources will not always be available domestically; international collaboration and co-operation are needed to channel them, particularly to least developed countries and small island developing states. The holistic global policy framework is discussed in Section 4.4.

4.1 CROSS-CUTTING POLICIES ENABLING THE ENERGY TRANSITION

A range of cross-cutting policies is necessary to provide enabling conditions for the accelerated deployment of energy transition solutions in all technological avenues (summarised in Table 4.1). Governments need to raise their energy transition ambitions while considering locally available renewable energy resource potential and multiple socio-economic and climate objectives. Ambitions should be accompanied by specific renewable energy targets and embedded within long-term plans that include phasing out fossil fuel assets. Among other measures, a fiscal system is needed that facilitates the adoption of energy transition solutions while disincentivising new investments in fossil fuel technologies and supporting a phase-out aligned with the 1.5°C Pathway. Policies and measures are also needed to facilitate access to finance, foster innovation and raise awareness among consumers – and citizens in general – to support the uptake of transition-related technologies.

Governments need to raise their energy transition ambitions while considering locally available renewable energy resource potential and multiple socio-economic and climate objectives.

TABLE 4.1 Overview of cross-cutting policies to enable the energy transition

OBJECTIVE	EXAMPLES OF MEASURES	COMMENTS
Raise ambition in commitments to the energy transition	Net zero targets can be seen in legislation in Denmark, France, Hungary, New Zealand, Sweden and the United Kingdom.	Targets should go beyond the power sector to include the energy needed for heating and cooling and transport, and for specific solutions and technologies, such as green hydrogen.
Phase out fossil fuels	Many European countries (*e.g.*, Denmark, France, Finland, Hungary, Italy, Portugal, Slovenia, the United Kingdom) have announced a plan to phase out coal power plants by 2030.	A holistic policy framework is necessary to address the issue of fossil fuel as a stranded asset and its socio-economic implications.
Eliminate distortions and incentivise energy transition solutions	Sweden's taxation of fossil fuels.	Policies (that may include fiscal policies such as carbon pricing) should be implemented with careful consideration of broader social and equity issues, particularly for low-income populations.
Facilitate access to finance	The Brazilian Development Bank offers a loan supporting biomass co-generation projects.	Public financing can facilitate the adoption of energy transition solutions. Interventions range from the public ownership of transition-related assets, to unlocking private sector participation and supporting just transition measures.
Foster innovation	Direct funding to research and development in energy transition technologies (*e.g.*, fast-charging infrastructure, green hydrogen linked with industrial use).	Enabling policies can further innovation across various dimensions of technology, infrastructure, financing, business models, market design and regulation, as well as governance and institutional frameworks.
Raise awareness among consumers and citizens in general	The campaign HeatSmart Northampton raises public awareness and promotes the installation of heat pumps in a town in the state of Massachusetts (United States).	Consumers and citizens play a big role in the energy transition: they influence governments and corporations to move faster in their decarbonisation plans and make proactive choices regarding their energy consumption and sources.

4.1.1 Raise the ambition of commitments to the energy transition

The past two years have been significant for the energy transition with a number of countries raising net zero commitments. More than 12 countries and the European Union passed or proposed laws around net zero emissions and have earmarked significant financial resources for green recovery plans with renewables as a key pillar, and around 20 countries have placed net zero targets in policy documents (Table 4.2). In April 2021, the United States hosted a Leaders' Summit on Climate ahead of the 26th UN Climate Change Conference of the Parties (COP26) and vowed to reduce emissions by at least 50% by 2030, more than doubling its prior commitment under the Paris Agreement (The White House, 2021). Brazil, Canada and Japan followed with their own commitments.

TABLE 4.2 Jurisdictions with net zero targets as of the first quarter of 2021

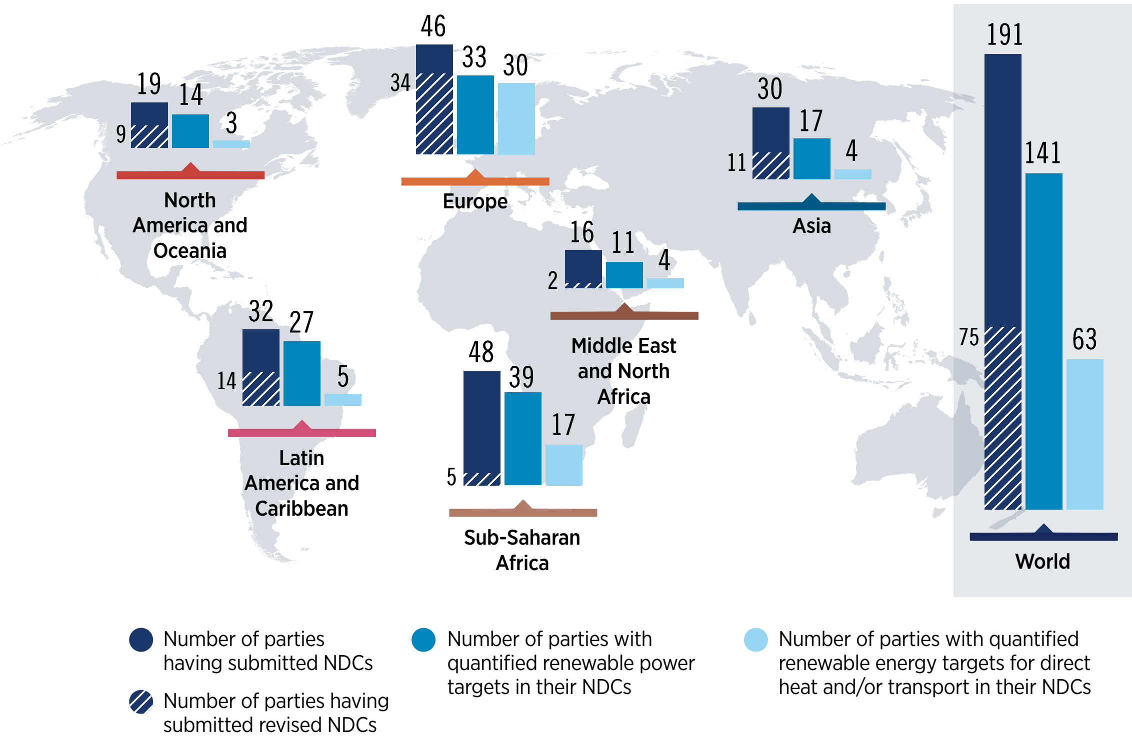
	Juristiction (by target year)
Achieved	Bhutan; Suriname
In law	Sweden 2045; Denmark 2050; European Union 2050; France 2050; Germany 2045; Hungary 2050; New Zealand 2050; United Kingdom 2050
Proposed legislation	Canada 2050; Chile 2050; Fiji 2050; Republic of Korea 2050; Spain 2050
In policy document	Finland 2035; Austria 2040; Iceland 2040; Andorra 2050; Brazil 2050; Costa Rica 2050; Ireland 2050; Japan 2050; Marshall Islands 2050; Norway 2050; Panama 2050; Portugal 2050; South Africa 2050; Switzerland 2050; Slovenia 2050; United States 2050; Vatican City 2050; China 2060; Kazakhstan 2060

Source: ECIU, 2021.

Countries around the world need to be increasingly ambitious in their pledges to scale up renewables and cut energy-related carbon dioxide (CO_2) emissions while also reaping significant socio-economic benefits. But net zero and ambitious targets are not immediately feasible for all economies. Nationally Determined Contributions (NDCs) are being revised more than five years after the signing of the Paris Agreement. As of the first quarter of 2021, 75 parties to the Paris Agreement had already submitted their revised NDCs. Of the total 191 parties having submitted NDCs, 141 (or 74% of the total) included quantified renewable energy targets for the power sector, while only 63 parties (33%) included targets for direct heat and transport, thus leaving the potential of renewables in end uses largely untapped (Figure 4.2). The NDCs, while representing vital national focus on the energy transition and climate action, are collectively insufficient to achieve the 1.5°C Pathway.

Renewable energy targets are key drivers of policies, investment and development, as they provide clear indications of the intended deployment and timeline envisioned, which are important signals to investors. As of October 2020, 160 countries had national-level targets for renewables in the power sector, compared to 49 countries with targets for heating and cooling and 46 for transport (REN 21, 2020).

FIGURE 4.2 Renewable energy components of NDCs, as of the first quarter of 2021

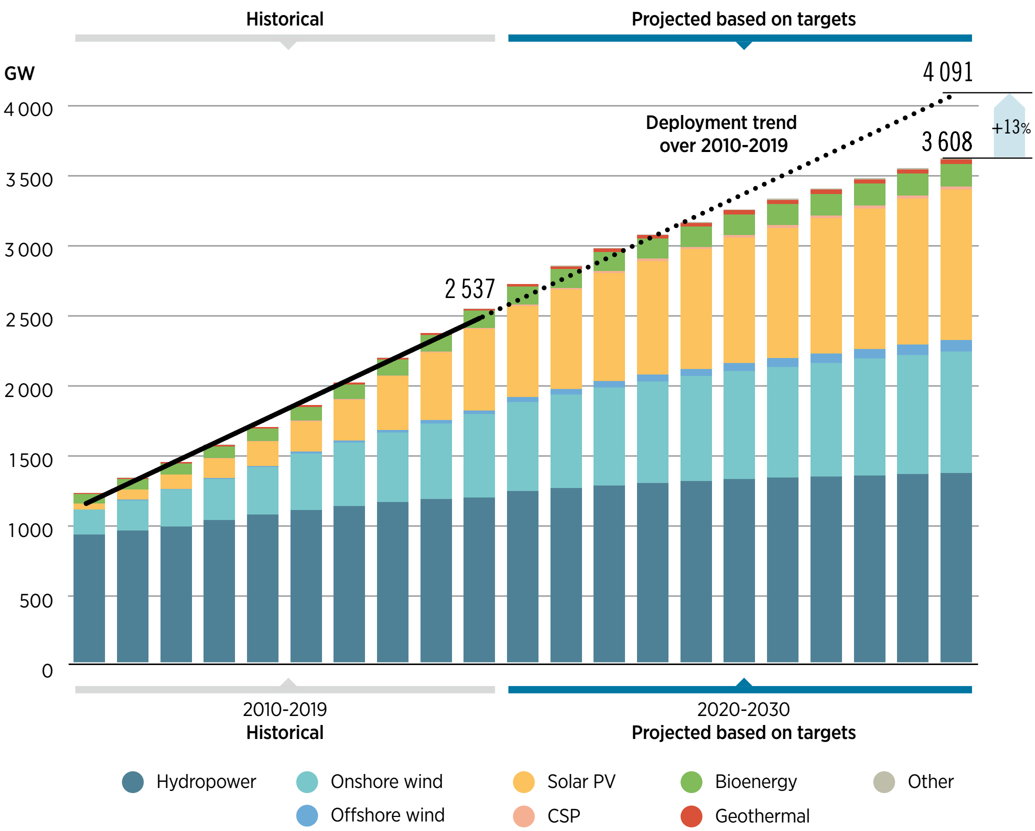


Source: Updated from IRENA (2020l).

Note: NDCs = Nationally Determined Contributions.

Over 60% of renewable energy targets for the power sector were already achieved at the end of 2019, leaving about 1 TW of renewables yet to be installed globally. As shown in Figure 4.3, existing renewable power targets fall short of actual deployment trends observed over the past decade. If renewable power installed capacity were to grow at the same pace as during 2010–2019, global renewable power capacity would reach 4 091 GW in 2030 – 13% higher than the level expected through target implementation (IRENA, forthcoming-a). But under IRENA's 1.5°C Pathway, the installed capacity of renewable power would need to reach 10 771 GW by 2030 (see Chapter 2) – more than double the amount installed to meet the targets noted.

FIGURE 4.3 Global installed capacity of renewable power: historical trends and future projections based on targets



Source: IRENA, forthcoming-a.

Note: CSP = concentrating solar power; GW = gigawatt; PV = photovoltaic.

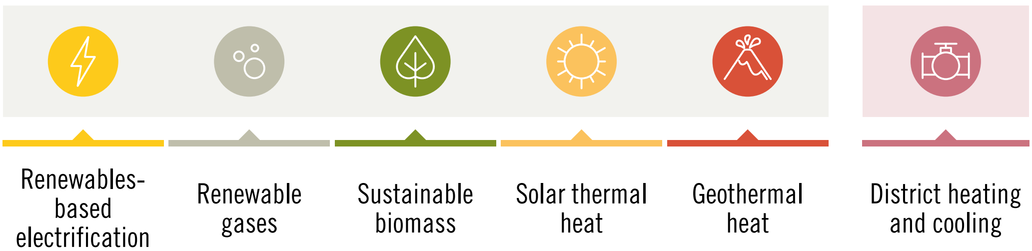
As noted earlier, national renewable energy targets have so far focused mainly on the power sector. Policy makers need to define more holistic targets covering all end-use sectors, including heating and cooling and transport, as well as specific solutions such as green hydrogen (Section 4.2.4). These targets form the basis to establish long-term integrated energy planning strategies discussed in the following section.

4.1.2 Develop a long-term energy transition plan

Accelerating the energy transition and maximising its benefits require an integrated energy planning approach that combines targets and commitments with holistic and long-term plans including the deployment of energy transition technologies, the phasing out of fossil fuels and the thorough consideration of their socio-economic impacts. An integrated long-term plan should be developed in coordination between different ministries (*e.g.*, energy and environment or climate change).

For heating and cooling, for example, cross-sectoral planning should integrate the transition with plans for other sectors (*e.g.*, power and industry). The energy plan must consider the different transition pathways including electrification, the deployment of green gases, sustainable biomass, solar thermal and geothermal heat, and district heating and cooling among key enabling infrastructure (Figure 4.4). The plan must be based on specific needs, macroeconomic conditions, availability of resources, the infrastructure already in place, and the level of development, accessibility and cost of technologies. Developing and implementing an integrated long-term plan require strong co-ordination and a robust institutional structure. This is especially the case when it comes to electrification with renewables, as it calls for the synchronisation of the deployment of renewable power plants with measures to deploy electricity-powered technologies in the transport and heating sectors in a timely fashion (Section 4.2.3).

FIGURE 4.4 **Solutions and enabling infrastructure for the energy transition in heating and cooling**



A long-term, integrated energy plan is also necessary to co-ordinate the deployment of renewables-based solutions with measures to raise energy efficiency and develop the needed infrastructure, while minimising stranded assets. For example, district energy networks are long-term investments and they are affected by changes in heating and cooling demand resulting from efficiency gains. Therefore, to align the strategies of district heating infrastructure and buildings is a must (IRENA, IEA and REN21, 2020). This was underlined by the European Union's modification to the Energy Performance of Buildings Directive, requiring synergies between renovation of buildings and investments in district heating systems (European Commission, 2021b) (Box 4.1).

BOX 4.1 Integrating innovation in buildings with district energy networks in the European Union

Buildings account for the largest share of energy consumption (40%) in the European Union (EU) and contribute to over a third of greenhouse gas emissions. The majority of buildings are over 50 years old and energy inefficient, and much of this stock will continue to exist in 2050 – the target year for the EU to become climate neutral. While the renovation of buildings has been a priority of EU climate actions, progress remains slow with only about 1% of the stock being renovated annually.

All EU member countries are required to publish a long-term building renovation strategy for 2050, as part of the "renovation wave" initiative of the Green New Deal. The renovation strategy supports greater energy efficiency and the integration of renewables in the building stock. The long-term nature of the strategy provides signals regarding the potential for investments in district heating and cooling networks, by outlining the expected demand in buildings after renovation.

Source: European Commission, 2020a, 2021b.

Based on the long-term energy plans, investments are needed to upgrade existing and develop new infrastructure, often as a pre-requisite to attracting private investments in energy-transition-related solutions. Those are discussed in this chapter, in sections dedicated to each of the technological avenues of the energy transition. An integrated energy plan can help minimise stranded assets for a given climate ambition by developing national strategies that leverage existing infrastructure. Examples include utilising existing district heating and cooling networks to deploy renewables-based solutions in cities, and repurposing parts of existing gas grids to transport green hydrogen. Synergies with the oil and gas industry can be leveraged. The offshore wind energy sector, for instance, can build on existing assets in the offshore oil and gas sector in different value chain segments, including foundations, array cables, substation structures, steelwork and cables (IRENA, 2018a).

Phasing out fossil fuels represents an important component of the energy transition.

4.1.3 Phase out fossil fuels

Phasing out fossil fuels represents an important component of the energy transition as discussed in Chapter 1. To reduce stranded assets, governments should halt the development of planned or new fossil fuel infrastructure. This can also send positive signals to other countries with similar contexts. The Government of Montenegro's announcement that it would stop the development of the second block of the coal power plant of Pljevlja, for example, drove the cancellation of a reconstruction plan for a coal power plant in North Macedonia and a new project in Kosovo* (CAN, 2020).

Some assets will need to be phased out, including fossil fuel upstream supply infrastructure, power plants, and fossil-based heating and cooling appliances or transport modes that need to be replaced. Many European Union countries (including Denmark, France, Finland, Hungary, Italy, Portugal and Slovenia) and the United Kingdom have announced a plan to phase out coal power plants by 2030; Austria and Sweden successfully phased them out by 2020 (Beyond Coal, 2021). Some Chinese cities including Suzhou city aim to replace all inefficient coal boilers with electric alternatives; and European cities including Athens and Madrid have announced plans to phase out petrol and diesel cars by 2025 (IRENA, 2021e, 2021f). As such plans are implemented, provisions should be made to ensure a just and fair transition and specifically to protect workers and communities. A dialogue involving all key stakeholders should be undertaken to decide how to address stranded assets.

A holistic policy framework is necessary to address the issue of fossil fuels as stranded assets and its socio-economic implications, requiring a series of measures further discussed in Sections 4.3 and 4.4. One among them is the compensation approach followed as countries seek to phase out fossil fuel assets earlier than foreseen, and to ascertain support needed for operators and communities, such as in Germany (Box 4.2).

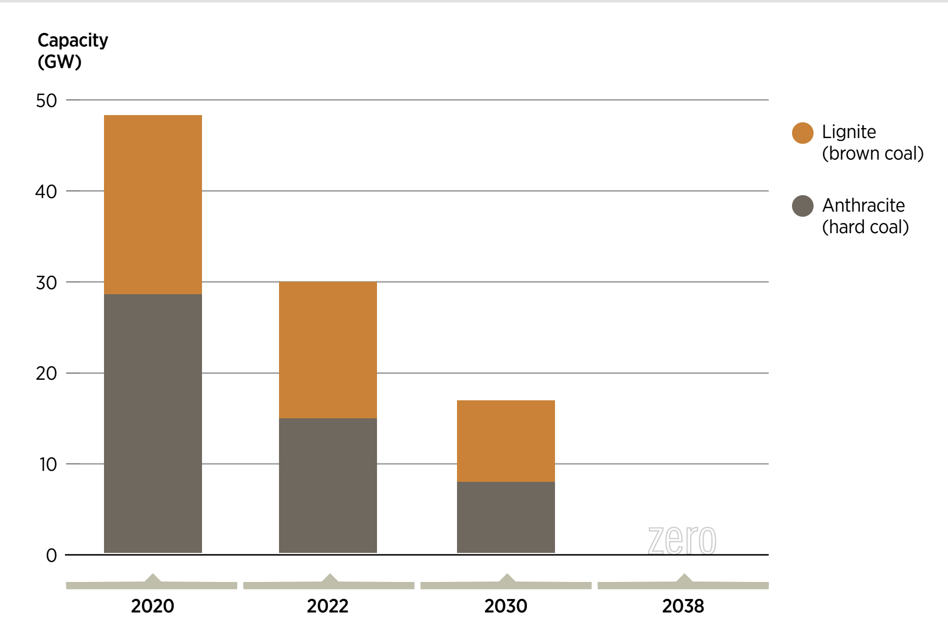
* This designation is without prejudice to positions on status and in line with the United Nations Security Council Resolution 1244 (1999).

BOX 4.2 Germany's tender for coal being phased out by 2038 as part of its green recovery plan

In 2020, the Coal Phase-Out Act (the Act to Reduce and End Coal-Powered Energy and Amend Other Laws) entered into force as part of Germany's green recovery plan. The act aims to gradually reduce and eventually phase out the use of coal-based power generation by 2038. It stipulates that no new coal-based plants may begin operations after August 2020, apart from those that already hold licenses. The phase-out is expected to be carried out in three stages (Figure 4.5).

The act offers financial compensation to operators of coal-fired plants for early retirement. The reduction of hard-coal power is to be achieved first by voluntary reductions offered by the plant operators and, after 2027, by legally mandating the reduction. To keep compensation to the minimum needed, the act set up competitive tenders where operators may offer capacity volume reductions and receive financial compensation in return. The plan was to auction 4 GW in 2020 and 1.5 GW in 2021 with non-awarded capacities in 2020 added to auctions in 2021. The auction is also designed to avoid the closure of power plants that are essential for network stability.

FIGURE 4.5 Phase-out of coal in Germany by 2038



Source: Bundesnetzagentur, 2021.

Note: GW = gigawatt.

The first auction was held in September 2020 with a pre-determined cap on the compensation set at EUR 165 000/MW (about USD 194 000/MW) net nominal capacity. The available financial compensation decreases each year to offer an incentive to decommission a plant earlier. After 2027, no financial compensation will be paid to plant operators that will all be forced to shut down. The German Federal Network Agency determines a maximum tender volume for each auction and uses a procedure set out in the act in case there are too many bids. Table 4.3 presents details of the first two rounds.

In addition, the Structural Support for Coal Regions Act provides lignite-coal regions with financial aid of up to EUR 14 billion (about USD 11.86 billion) and hard-coal regions up to EUR 1.09 billion (about USD 923 million) to deal with structural changes and to secure employment. The act also provides up to EUR 26 billion (about USD 22.02 billion) for highway and rail infrastructure improvement or expansion and creation of up to 5 000 additional jobs in federal agencies in the coal regions.

Sources: Gesley, 2020; European Commission, 2020b.

TABLE 4.3 Results of auctions for coal plant phase-out in Germany

ROUND	CAPACITY AUCTIONED	CAP ON PRICE	CAPACITY AWARDED	WINNING BIDS	REQUIREMENTS
2020	4 000 MW	165 000 EUR/MW	4 788 MW	11 bids accepted (the largest for 875 MW) with a total of EUR 317 million (USD 385.6 million). Volume-weighted average award of EUR 66 259/MW with bids ranging from 6 047 to 150 000 EUR/MW	Plants retire from the wholesale market beginning 2021 and the units remain available only to transmission system operators for balancing until June-end. Operators cease coal-based power generation from July.
2021	1 500 MW	155 000 EUR/MW	1 514 MW	Three bids for 757 MW, 690 MW and 67 MW. Bids ranged from 0 to 59 000 EUR/MW	Operators to cease coal-based generation by December 2021. Auction open to installations in the south of Germany (not eligible in first round).

Sources: Shumkov, 2020; Petrova, 2021.

Note: MW = megawatt.

4.1.4 Eliminate distortions and incentivise energy transition solutions

Distortions that favour the uptake of fossil fuels by market structures need to be eliminated and a fiscal system established that actively supports the adoption of energy transition solutions, while disincentivising new and existing traditional solutions not aligned with climate ambitions. This involves phasing out existing fossil fuel subsidies, and levying the environmental, health and social negative externalities of fossil fuels to remove market distortions as well as existing support for the fossil fuel industry (see Chapter 5).

Fiscal policies, including carbon pricing policies, should be implemented and adjusted to enhance the competitiveness of renewables-based solutions against fossil fuels (discussed further in Section 5.1). In Sweden, the taxation of fossil fuels has been a major driver for renewable heat, whereas low natural gas prices (reflecting subsidies to fossil fuel industries and unlevied negative externalities) hobble the competitiveness of renewable heat options in the United Kingdom and the United States (IEA, 2018).

However, as with the phasing out of fossil fuel subsidies, such interventions should be preceded by a careful assessment of their social and equity dimensions, particularly their effects on low-income populations, to ensure that they do not worsen energy poverty (Box 4.3) or have other socially regressive effects. Allaying these concerns by exempting certain household groups or energy-intensive industries can compromise the viability of schemes. Instead, it may be more in line with long-term de-carbonisation objectives to provide dedicated support for low-income consumers or other highly affected parties to help them shift towards low-carbon solutions (see Section 4.5).

As with the phasing out of fossil fuel subsidies, carbon pricing policies should be preceded by a careful assessment of their social and equity dimensions.

BOX 4.3 Addressing energy poverty

The term "energy poverty" covers a broad spectrum of negative effects on well-being, due to affordability challenges, or a lack of or insufficient access to modern energy solutions. In a situation of energy poverty, a household is physically and/or financially unable to secure a level and quality of domestic energy services sufficient for its social and material needs. This situation is often accompanied by the use of dirty fuels (e.g., kerosene, traditional fuelwood), excessive time spent collecting them and low consumption of energy.

A definition of energy poverty accepted worldwide is still missing. Without a unified definition, the number of households living in this situation cannot be properly quantified. Yet, statistical data that describe some of the effects of energy poverty can help clarify the issue.

Energy poverty exists in every part of the world. In the Western Balkans, for instance, one out of three households is unable to keep adequately warm. Households with an income below 60% of the national median are particularly at risk (Figure 4.6). As a comparison, fewer than one out of ten households in the European Union faces the same challenge (but up to two out of ten among poor households).

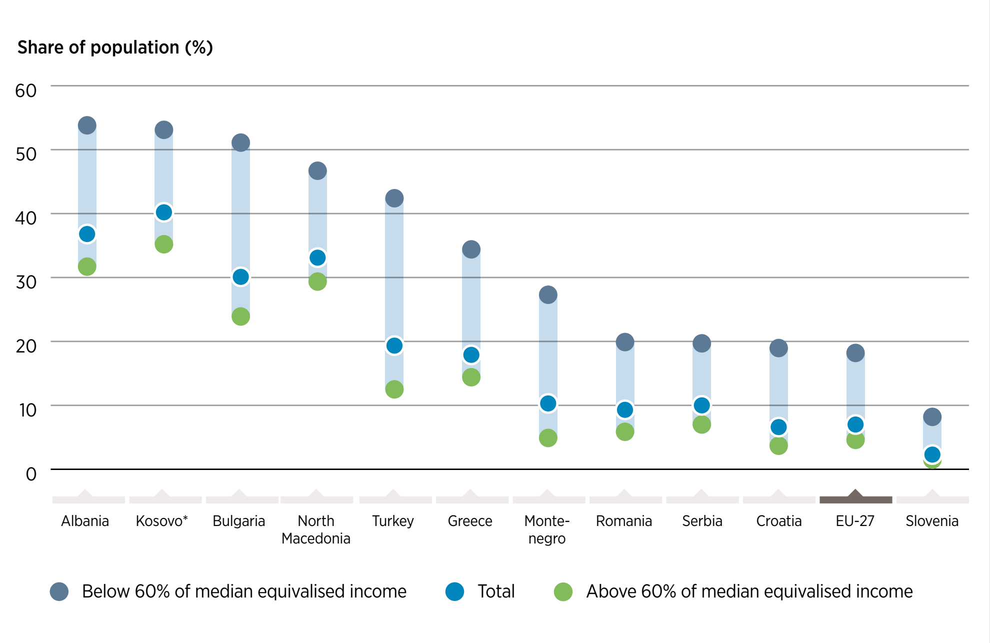
Estimates indicate that 3 million households (out of 5 million) in the Western Balkans use outdated woodburning devices, a main indicator of energy poverty. The high dependence on biomass and poor regulatory mechanisms also endangers local forest resources, which are subject to illegal logging and black-market sales. The use of traditional biomass substantially increases indoor air pollution levels, which in Southeast Europe caused around 23 000 preventable deaths in 2016.

Governments in the region have taken steps to address energy vulnerability. They have adopted definitions of "vulnerable customers", and many provide some form of assistance to this population, mainly in the forms of cross-subsidisation, discounts on energy bills and protection from disconnection.

Source: Energy Poverty Observatory, 2020; IRENA, 2019e.

Energy poverty exists in every part of the world.

FIGURE 4.6 Share of households unable to keep home adequately warm, by income level, in selected countries, 2019 (%)



Source: Energy Poverty Observatory, 2020.

* This designation is without prejudice to positions on status and in line with the United Nations Security Council Resolution 1244 (1999). Data for Kosovo are for 2018.

4.1.5 Facilitate access to finance

Public financing will play a crucial role in facilitating the adoption of energy transition technologies and solutions. Depending on local contexts, its role could vary from public ownership of transition-related assets, to unlocking private sector investments in energy transition technologies. This is especially needed in contexts with high risks where attracting private investments is challenging. Relevant risks include country risks (related to politics, policy and currency), contractual risks (liquidity, counterparty and refinancing risks) and technical risks. As discussed in Chapter 3, risk mitigation instruments can be an effective tool to improve the risk-return profile of projects and increase their attractiveness among private investors.

Public funding is also needed to reduce technical risks associated with specific technologies, project performance, resources and infrastructure. To reduce the risk of geothermal exploration, for example, government support measures include collecting and sharing geothermal data on public platforms, providing insurance against exploration risks and offering loan guarantees and grants to reduce the risk represented by the sunk cost of well drilling. The Government of the Netherlands, for instance, provides funds for geothermal heat projects set out by the Geothermal Heat Action Plan. Government funds are used to support risk insurance for the drilling of geothermal heat, to invest in software (ThermalGIS) for geothermal exploration, as well as grants and other financial schemes (Government of the Netherlands, 2021).

Bioenergy projects could face additional difficulties securing financing due to supply chain risks (*e.g.*, unstable feedstock supply, potential negative impacts on forestry or food prices). Specific public funds are needed to facilitate investment from commercial entities. For example, the Brazilian Development Bank provides loan support for biomass cogeneration projects, also allowing commercial banks and capital markets to step in (IRENA, forthcoming-b).

In the access context, significant investments are needed mainly to accelerate the adoption of decentralised renewable energy solutions to meet electricity and clean cooking needs. Tailored financing instruments are required to meet end-user and enterprise needs, along with investments (primarily public) in an enabling ecosystem featuring appropriate policies and regulations, capacity building and market linkages. IRENA analysis finds that investments in the off-grid sector, although growing, are heavily concentrated in certain regions, countries and technologies (IRENA and CPI, 2020). Greater public and private financing needs to be mobilised and made more equitably accessible to end-users and enterprises through local financing institutions.

Greater public and private financing needs to be mobilised and made more equitably accessible to end-users and enterprises.

4.1.6 Foster innovation

As indicated in Chapter 2, systemic innovation will play a central role to drive down costs and ramp up the pace of the energy transition. A number of enabling policies can strengthen the innovation process across its various dimensions of technology, infrastructure, financing, business models, market design and regulation, as well as governance and institutional frameworks. The scope of innovation extends far beyond technology supply.

Research, development and demonstration policies relate to direct funding of research and development across a wide range of energy transition technologies (*e.g.*, fast-charging infrastructure, green hydrogen linkages with industrial use) that are at different stages of market maturity, as well as support of demonstrations and piloting to create commercial-scale solutions.

A **deployment-oriented innovation approach** is needed for the success of the energy transition, particularly as the pathway from invention to mainstream technology may take long. The Innovation Toolbox (www.irena.org/innovation/Toolbox) developed by IRENA shows how 30 concrete innovations in technology, market design, business models and system operation can be used to transform country power systems by increasing flexibility. Power systems' flexibility is a priority for this decade, as an enabler of large shares of solar and wind. In terms of enabling technologies, battery storage is at the centre of present energy transition efforts.

Policies can also help to deploy enabling infrastructure (*e.g.*, charging infrastructure for electric vehicles) faster. This highlights another priority for this decade – streamlining infrastructure planning and permitting. **New business models** come into play, including aggregators and peer-to-peer trading platforms supported by digital technologies that enable small players to reap the full benefits of their rooftop solar systems, while system operators can benefit from the services of distributed energy resources (IRENA, 2020k). Such new business models are now widely deployed. In some jurisdictions, laws and regulatory regimes need to be adjusted to allow such innovations to be scaled.

Innovation in market design has proven critical to accelerate the transition (IRENA, 2017c). New technologies come with new types of services that can be provided to energy systems, but those services need to be properly monetised via adjustments to market design (*e.g.*, greater time or geographic resolution of energy prices).

For sectors that cannot be directly electrified, green hydrogen can play a key role, if electrolysers can be operated flexibly and their cost falls enough to warrant flexible operation. This is an example of an emerging technology option that can help to revolutionise the way we produce and consume energy. Meanwhile, innovations are required across the full production, shipment and deployment chain. Finally, policies can facilitate innovation through the deployment of new standards and certification processes, as well as through international collaboration by promoting sectoral agreements that accelerate deployment of new technologies.

4.1.7 Raise awareness among consumers and citizens

Consumers and citizens play a big role in the energy transition. On one hand, they can influence governments and corporations to move faster in their decarbonisation plans. For example, customer, shareholder and staff demand has been identified as one of the main drivers for corporate sourcing of renewable heat (IRENA Coalition for Action, 2020a). On the other hand, citizens make proactive choices regarding their energy consumption and sources.

Sharing information and raising awareness through public campaigns are vital for citizens to adopt clean solutions and behavioural changes in line with reducing energy consumption (Section 4.2.2). In heating and cooling, for example, government actions – at the national and city levels – to raise awareness regarding the potential and benefits of renewable solutions are essential to stimulate interest and strengthen confidence among potential consumers and relevant actors. South Africa launched the Solar Water Heater Campaign to increase public awareness while similar policies helped Barcelona (Spain), Rizhao (China) and Cape Town (South Africa), among other cities, to promote solar thermal solutions (IRENA, IEA and REN21, 2020).

Active engagement of consumers and citizens is important to integrate the complex dynamics of social systems within the energy transition. Holistic policies that address social feedback and concerns – for instance, those arising from the implementation of regressive policies (discussed further in Section 4.4) – are better perceived by society at large and contribute to improved energy transition outcomes for the society, economy and planet.

Active engagement of consumers and citizens is important to integrate the complex dynamics of social systems within the energy transition.

4.2 POLICIES TO SUPPORT THE TECHNOLOGICAL AVENUES OF THE ENERGY TRANSITION

While cross-cutting policies provide an enabling environment for the energy transition to move forward seamlessly, specific policies and measures are needed as well to increase the deployment of renewables, both in power and direct uses; promote energy conservation and efficiency; enable the electrification of end uses and support the development of green hydrogen and sustainable bio-energy. These are discussed further in this section and summarised in Table 4.4.

Specific policies and measures are needed to increase the deployment of renewables, promote energy conservation and efficiency, enable the electrification of end uses, and support the development of green hydrogen and the sustainable use of bioenergy.

TABLE 4.4 Overview of policies to support energy transition solutions

TECHNO-LOGICAL AVENUE	OBJECTIVE	EXAMPLES OF MEASURES	COMMENTS
Renewables (power and direct uses)	Deploy renewable energy in end uses	Subsidies for solar water heaters in China, Tunisia and Lebanon.	These policies include regulatory measures that create a market, as well as fiscal and financial incentives to make them more affordable and increase their cost competitiveness compared to fossil-fuel-based solutions.
	Deploy renewable energy in the power sector	Dedicated regulations for mini-grids in Nigeria, Kenya, Uganda, Zambia, Sierra Leone and Senegal.	The choice of instrument and its design should consider the nature of the solution (*e.g.*, utility scale, distributed, off-grid), the sector's level of development, the power system's organisational structure and broader policy objectives.
Energy conservation and efficiency	Increase energy conservation and efficiency in heating and cooling	In the United States, China, Canada and Japan, almost all space cooling activities need to meet mandatory Minimum Energy Performance Standards.	Energy efficiency policies such as strict building codes, support for building retrofits and appliance standards are critical for the energy transition in buildings and industrial processes.
	Increase energy conservation in transport	Vancouver (Canada), launched a city campaign to encourage cycling and reduce private car use.	Decarbonising the transport sector, among other measures, requires a shift from energy-intensive modes to low-carbon modes.
Electrification of end uses	Electrify heating and cooling	Denmark reduced the tax paid on electricity-based heat as part of the country's plan to be fossil fuel free by 2050.	Targets for renewable power should consider the rising demand from the electrification of end uses, in line with long-term decarbonisation objectives. Moreover, policies and power system design are needed to support electrification in achieving its potential for providing system flexibility.
	Electrify transport	Costa Rica set a target for 100% of vehicle sales to be zero emission by 2050, and Japan aims to have all cars be electric by 2050.	
Green hydrogen	Support the development of green hydrogen	By 2020, 12 countries and the European Union had implemented green hydrogen policies.	An enabling policy framework should consider four key pillars: a national green hydrogen strategy, priority setting, guarantees of origin and enabling policies.
Sustainable bioenergy	Ensure the sustainable use of bioenergy	The EU's revised Renewable Energy Directive (EU REDII) enhanced the sustainability criteria for bioenergy	Renewable energy is not exempt from sustainability concerns. Some of these concerns include greenhouse gas emissions related to land-use change, and impacts on air and water quality and biodiversity.

4.2.1 Deploy renewables (for power and direct uses)

Policy options supporting the deployment of renewable energy technologies and solutions vary according to the level of development of the sector. Instruments to deploy renewables have predominantly focused on the power sector since the early 2000s. With evolving market conditions and the changing maturity of technologies and markets, the instruments have adapted over time. For instance, the developments made to date have enabled many countries to transition from administratively set to competitively set pricing mechanisms for renewable power. As the share of renewable electricity has grown, integration, flexibility and power market design aspects have also come to the fore in policy making.

Instruments to support the direct use of renewables in heating and cooling and transport have so far not received the same level of policy attention, as is evident in target setting and deployment trends. Accelerating the pace and depth of the energy transition will require a continuing focus on the power sector, along with much greater policy efforts in the heating and cooling, and transport sectors. This section discusses policies to accelerate renewables' adoption across end-use sectors. For both power and direct uses, deploying renewables at the scale needed for the 1.5°C Pathway will require policies to integrate impacts across society and planet, and minimise any potential negative impacts. This issue is further discussed in Section 4.2.5 for bioenergy and Section 4.3.4 for solar photovoltaic (PV) and other transition technologies.

Accelerating the pace and depth of the energy transition will require a continuing focus on the power sector, along with much greater policy efforts in the heating and cooling, and transport sectors.

Deploy renewable energy in end uses

Policies supporting the deployment of renewable energy for heating and cooling and transport include regulatory measures that create a market for these technologies, as well as fiscal and financial incentives, such as subsidies, grants and tax credits, to facilitate adoption and make them more equitably accessible for all types of users.

Measures to create a market for renewable energy solutions

Policy makers need to establish dedicated, clear and long-term frameworks for the development of solutions such as solar water heaters and sustainable biofuels. Such frameworks can include **roadmaps, industrial strategies and specific targets.** For example, India is targeting 20 million square metres (m^2) of solar thermal collectors by 2022. Targets can also be set at the regional level. The Economic Community of West African States adopted the target to deploy solar thermal heating for around 50% of all health centres and schools, 25% of hotels and 25% of the agri-food industry by 2030 (ECREEE, 2015). The EU's revised Renewable Energy Directive to 2030 (RED II) aims for 14% of renewables in final energy demand of transport, including 3.5% from advanced biofuels produced from waste, residues and other cellulosic feedstocks (IRENA, forthcoming-b).

Targets for green gases are also emerging, especially with the increased interest in green hydrogen. France set a target to make 10% of the gas consumed in the country renewable by 2030; Denmark aims to make 100% of the gas injected into its grid renewable by 2035. Spain wants 25% of hydrogen consumed to be green by 2030. Section 4.2.4 presents a dedicated analysis of policies for green hydrogen.

Targets and roadmaps can be supported by **mandates**, such as for biofuel blending in Brazil, China, the European Union and the United States; or requiring the installation of solar thermal systems in new or existing buildings as in Kenya or Spain. Such mandates, like targets, can also be implemented at the city level (see Box 4.4).

City-level policies play a key role in creating a market for district heating and cooling and green gas services where guaranteed anchor loads are crucial for the development of the needed infrastructure. Mandating connections to district heating and cooling networks or renewable gas grids (where these exist) in new urban developments, public buildings and other opportune locations ensure a stable demand for the network and reduce investment risk. Such mandates have been introduced in Amsterdam (the Netherlands), Oslo (Norway), Belgrade (Serbia) and Abu Dhabi and Dubai (United Arab Emirates).

Policies to support renewables include regulatory measures that create a market for their adoption, and financial incentives to make them more equitably accessible for all users.

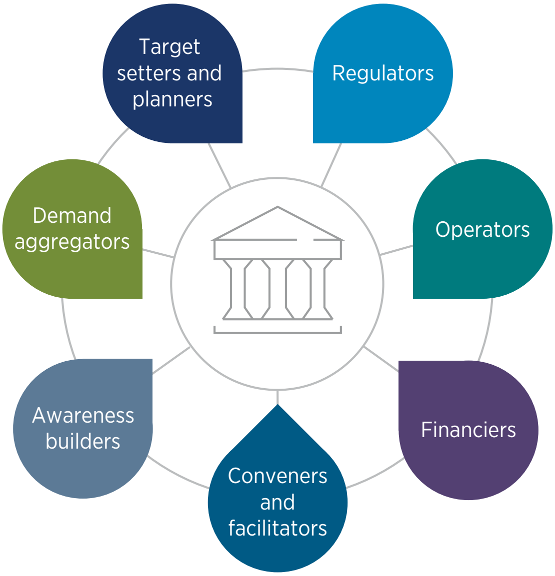
BOX 4.4 The role of cities in the energy transition in end uses

Cities play a major role in advancing the global energy transition. They account for around three quarters of global primary energy and contribute to 70% of greenhouse gas emissions. At the same time, residents of urban areas face higher rates of air pollution, mainly resulting from the use of fossil fuels – a key and urgent driver of the energy transition.

The energy transition in cities is a story of urban transformation. Renewables have far-reaching effects that go beyond the energy sector; they influence transportation, buildings, land use and a slew of other vital city sectors. The energy transition presents an opportunity to reimagine cities in a number of ways that benefit both people and the environment.

There are several roles cities can play in accelerating the deployment of renewables in end uses (Figure 4.7). Actions focus mainly on measures to promote the electrification of public transit and to curb the use of internal combustion engine vehicles in urban areas, solar thermal ordinances, and renewable heating and cooling mandates.

FIGURE 4.7 Roles of municipal governments in the energy transition



Sources: IRENA, 2021e, 2021f, 2021g, 2021h.

Financial and fiscal incentives for the increased adoption of renewables in end uses

Financial incentives are still required to increase the adoption of renewables in many jurisdictions. For heating and cooling, centralised solutions such as renewables-based district heating and cooling and decentralised solutions such as domestic solar water heaters are not always cost competitive compared to fossil fuels. Financial incentives can be provided as single-payment subsidies, grants or loans. France's Fonds Chaleur (Heat Fund), for example, offers subsidies for residential, commercial and industrial renewable heat, including small-scale biomass applications (EurObserv'ER, 2020). On a local level, Grenoble increased the Fonds Chaleur by adding local financial aid to small-scale projects (REN21, 2019). China, Tunisia and Lebanon provide subsidies for solar water heaters (IRENA, forthcoming-c). Germany's Market Incentive Programme provides low-interest loans for large-scale projects for district heating and industries and grants for small-scale renewable heat solutions (IRENA, IEA and REN21, 2020).

Fiscal incentives such as **tax credits, reductions** and **accelerated depreciation** are commonly used to support the energy transition in end uses. For heating and cooling, residents in the United States could receive up to USD 500 in tax credits for the installation of geothermal heat pumps, solar water heaters and other energy efficiency technologies (United States DoE, 2021). In transport, such incentives are needed to promote biofuel production, distribution and consumption, as well as research and development. In 2016, Argentina put in place tax exemptions for biodiesel production and Sweden reintroduced tax cuts for ethanol and biodiesel (REN21, 2017).

Fiscal and financial incentives typically benefit individuals and corporations that have the financial capacity to invest in such solutions (with some financial support), with the risk of leaving behind low-income households locked in traditional and less efficient solutions (*e.g.*, traditional biomass for heating and cooking or inefficient combustion engine vehicles) thus contributing to further energy poverty (Box 4.3). It is crucial that a holistic policy approach be adopted that considers and addresses the aggregate socio-economic implications of various energy transition policy actions. Provisions should be made to ensure that direct support reaches the lowest-income households. For example, the Government of New Zealand provides grants to cover 90% of the cost of heat pumps or efficient pellet/wood burners and insulation improvement for low-income homeowners through the "Warmer Wiki Homes" programme (EECA, 2021).

Regarding access, fiscal and financial incentives have played a crucial role in facilitating the adoption of renewables-based clean cooking solutions. Household biogas digestor programmes have benefited from an appropriate mix of grants, increasingly deployed as results-based financing and concessional loans. The Africa Biogas Partnership Programme, for instance, deployed over 70 000 biogas digestors across six countries in Sub-Saharan Africa through tailored financial incentives. Similarly, Viet Nam's national biogas digestor programme facilitated the deployment of over 250 000 domestic systems initially through household subsidies followed by a transition to results-based financing for suppliers to support long-term market development (IRENA, 2018b). Other clean cooking solutions, including improved cookstoves, benefit from tax exemptions and rebates thus improving affordability for households (WHO, n.d.).

Auction design should be tailored to country-specific conditions and broader policy objectives.

Deploy renewable energy in the power sector

Regulations and pricing instruments, together with fiscal and financial incentives, support the deployment of renewables-based power, while at the same time support measures are required to enable the electrification of end uses (see Section 4.2.3).

Regulatory and pricing instruments to support renewable power generation

Scaling up renewable energy adoption in the power sector requires regulatory and pricing instruments, which adapt as renewables become cost competitive compared to fossil-fuel-based electricity[2] in many more jurisdictions. The choice of instrument and its design should consider the nature of the solution (*e.g.*, utility scale, distributed, off-grid), the sector's level of development and the power system's organisational structure and broader policy objectives. Each instrument should be adopted with specific considerations.

Pricing policies such as feed-in tariffs and premiums can be administratively set, in which case they need to continuously adapt to changing market conditions. Regular tariff-level adjustment, such as through degression mechanisms, can help reflect the falling costs of a technology and its growing deployment. Otherwise, prices can be set through competition.

Auctions are being increasingly adopted to keep pace with falling technology costs and to deliver renewable electricity at competitive prices globally. By 2020, around 209 countries had adopted auctions (REN21, 2020), and by 2018, the global average prices from solar PV and onshore wind auctions had decreased by 77% and 36%, respectively, compared to 2010 (IRENA, 2019c). In addition to procuring renewable electricity cost-effectively, auctions can be designed to pursue broader policy objectives (Box 4.5). However, if not designed well, auctions can lead to underbidding and projects not being completed on time or at all, and in some cases, they risk favouring large players, and leaving the small and new players behind. To take advantage of the strengths of auctions and minimise the risks associated with their weaknesses, auction design should be tailored to country-specific conditions and broader objectives.[3]

2 IRENA (2021b) analysis presented in *Renewable Power Generation Costs in 2020* finds that more than 60% of the renewable capacity added in 2020 achieved lower power costs than the cheapest new fossil-fuel plants.

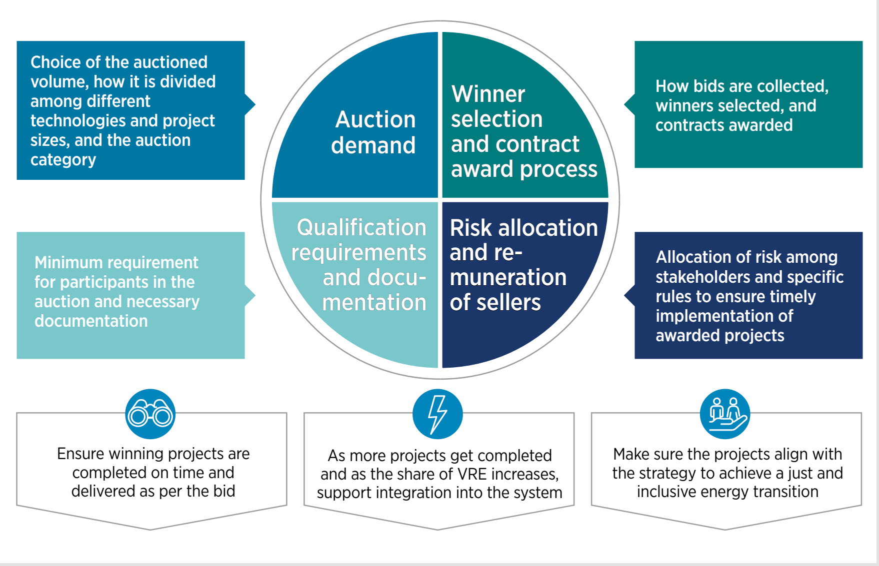
3 IRENA provides capacity building and policy advice to countries looking to design renewable energy auctions through the Policy Framework for the Energy Transition (PFET).

BOX 4.5 Auction design to support policy objectives beyond price

Auctions are flexible in their design and they can serve objectives beyond price as trade-offs are studied and choices are made regarding the design elements (Figure 4.8). Auctions can be designed to maximise socio-economic benefits, through the inclusion of small and new players, job creation, regional development and community benefits, and the development of local industries. South Africa was a pioneer in promoting economic development, especially in under-served regions, through qualification requirements and winner selection criteria that consider socio-economic development objectives.

Innovative auction design can also help address some of the challenges related to system integration as shares of variable renewable energy generation increase. Mexico has considered geographical allocation signals according to network integration feasibility and costs. India and South Africa have sought to concentrate renewable project developments in specific geographical areas, while hybrid technologies have been auctioned in Jordan (PV with storage), India (wind and PV) and Morocco (concentrating solar power and PV).

FIGURE 4.8 Auction design for objectives beyond price discovery



Source: IRENA, 2019c.

Note: VRE = variable renewable energy.

Competitive procurement is also adopted in corporate purchase programmes for renewable power, enabling the buy-in of industry into renewables and accelerating investment in the energy transition. Next to supporting an effective system for the issuing and tracking of energy attribute certificates, energy market structures that allow for direct contracting between companies and renewable energy suppliers support the further uptake of corporate sourcing of renewables.

For non-utility-scale projects, such as off-grid systems (Box 4.6) and grid-connected distributed solutions, tailored regulatory and pricing instruments are needed. Distributed generation can be supported through net metering and net billing. However, careful consideration is needed to avoid jeopardising the system's cost recovery and prevent cross-subsidisation among customers who self-consume and those who do not. Indeed, these and other kinds of misalignments between the expected and the actual outcome of power system policies and regulation are bound to increase as the energy transition progresses, if no measures are taken to redesign the power system's organisational structure (see In focus section).

BOX 4.6 Policies for off-grid renewable energy solutions

Facilitating the deployment of off-grid renewable energy solutions, such as mini-grids and stand-alone systems, to improve modern energy access requires dedicated policies and regulations.

In the specific case of stand-alone systems, policies can strongly influence the accessibility and sustainability of such solutions for rural communities. Fiscal incentives, such as import duty and value-added tax exemptions, are often introduced to incentivise market development; these directly improve the affordability of stand-alone systems (IRENA, 2019f). Other supportive measures include levelling the playing field, introducing quality standards and establishing dedicated consumer/enterprise financing channels as part of a broader programme.

Scaling up renewable energy mini-grids requires dedicated regulations to address key areas such as licensing and permitting requirements, tariff-setting frameworks and the implications of the arrival of the main grid (IRENA, 2018c). A growing number of countries have introduced dedicated regulations meant to scale up mini-grids, including Kenya, Nigeria, Senegal, Sierra Leone, Uganda, and Zambia (UNIDO, 2020). Moving beyond addressing deployment and investment risks, policies also need to address aspects related to capacity building and linkages between the sector and productive end uses (see Section 4.3). All of these have a strong bearing on the scalability of off-grid solutions and the socio-economic outcomes of deployment policies.

Fiscal and financial incentives for renewables-based solutions

Fiscal and financial incentives such as tax incentives, subsidies and grants complement regulatory and pricing mechanisms and are needed to improve access to capital, lower financing costs and make energy transition solutions more equitably accessible for all potential end users.

Reductions in sales, energy, value-added or other taxes on renewable electricity technologies have been instrumental in kick-starting deployment in some countries in Southeast Asia and sub-Saharan Africa (IRENA, IEA and REN21, 2018), mainly in the access context (Box 4.6). Production and investment tax credits were instrumental in driving the development of solar and wind in the United States. But since their initial inception, federal renewable tax credits have expired, been extended, modified or renewed numerous times, creating uncertainty and multiple boom-and-bust cycles in the industry. When implemented, tax credits should be long term to reduce uncertainty and attract stable investments.

Capital subsidies for renewable electricity technologies are needed to reduce upfront capital costs in early stages of deployment (or when targeting low-income end-users), after which they may be replaced by other forms of incentives, including performance-based subsidies. In Nepal, capital subsidies offered in 2013 covering 40% of project capital costs – along with a soft loan covering another 40% – were phased out to give way for generation-based support in 2016, thereby increasing the efficiency of systems (Climatescope, 2016). Grants are needed to fund research and development, demonstration projects and feasibility studies to support the wider deployment of technologies and the integration of variable renewable energy into the power system (see Section 4.1).

Fiscal and financial incentives complement regulatory and pricing mechanisms. They improve access to capital, lower financing costs and make energy transition solutions more equitably accessible for all potential end users.

Public investments in enabling infrastructure and flexibility mechanisms

Depending on local contexts, public investments will play a fundamental role in upgrading and expanding power grids and deploying power system flexibility to enable the integration of greater shares of variable renewable energy (VRE).[4] In liberalised power market settings, private investments particularly in flexibility options may still be attracted where appropriate organisational structures exist within the power sector (see In focus section). The flexibility options include the deployment of short- and long-term storage solutions (pumped hydropower, chemical batteries, hydrogen storage and thermal storage), demand-side resources (such as industrial loads, or residential ones, managed by aggregators), interconnections among different power pools and dispatchable renewable power plants. Electrification will require strategies for the adoption of digital solutions to unlock the hidden flexibility of electric loads, control the grids remotely and provide a more granular visibility over grid status to power system participants. The new, flexible, decentralised power system will need an organisational structure fit for the renewable energy era.

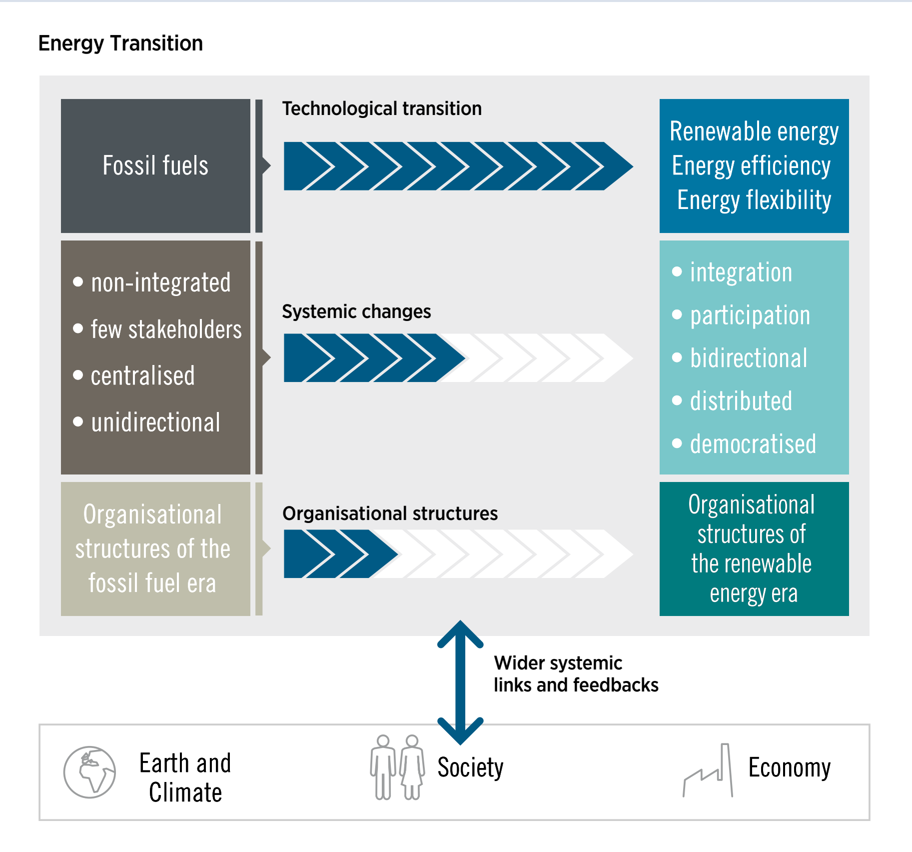
The new, flexible, decentralised power system will need an organisational structure fit for the renewable energy era.

4 For an exhaustive discussion of flexibility and the role of governments in creating the enabling frameworks for power sector transformation, see IRENA (2019a) Innovation Landscape for a *Renewable Powered Future: Solutions to Integrate Variable Renewables*, and the related innovation toolbox: www.irena.org/innovation/Toolbox.

In focus – the organisational structure of power systems for the renewable energy era

A smooth energy transition comprises a technological transition, systemic changes and the reorganisation of the power system. While the technological transition and systemic changes are relatively well understood, the reorganisation of the power system lags behind (Figure 4.9), held back by implicit assumptions that current organisational structures are appropriate for the renewable energy era. Power system organisational structures were designed with the blueprint of fossil fuel technologies. But the energy transition is transforming how electricity is produced, transmitted and consumed. Consequently, the interactions between the different elements of the power system (organisational structures, technologies and policies) and with the wider energy, socio-economic and planetary systems are also changing.

FIGURE 4.9 Unequal advance in different transition layers, with organisational structures lagging behind



Both regulated and liberalised power systems face similar transition-related challenges. Merely adjusting and fixing, bit by bit, the organisational structures of current power systems will not suffice, and might in fact lead to additional misalignments producing unwanted effects able to derail the energy transition (see Box 4.7).

This is not new. Energy systems are set up to provide energy services to society, but in delivering those services, undesirable impacts on societies have been produced. Important misalignments have, for instance, led to climate change and air pollution. This results from organisational structures of the fossil fuel era not properly aligning the costs, price and value dimensions of energy. While the energy transition itself is expected to mitigate both climate change and air pollution, as the transition progresses, new fundamental misalignments arise (IRENA, 2020d), with potentially severe consequences, if unaddressed.

Energy systems are set up to provide energy services to society, but in delivering those services, undesirable impacts on societies have been produced.

BOX 4.7 Definitions of power system organisational structure and misalignments

Power system organisational structure refers to the structural elements of both liberalised and centrally-planned power systems that guide the interactions between all agents in the procurement and cost allocation of electricity and power services. Structural elements encompass regulations, markets and ownership regimes.

Organisational structures should be properly informed and guided by value, costs and prices considerations. The term “power market” is equivalent to “power system organisational structure” for a liberalised power system.

Misalignment: represents any conflicting interaction of different components within the power system (be they related to technology, policies, organisational structures, or others) with each other or with elements in the wider energy, socioeconomic and planetary systems, producing undesired effects in the pursue of a just and ambitious energy transition.

The misalignments

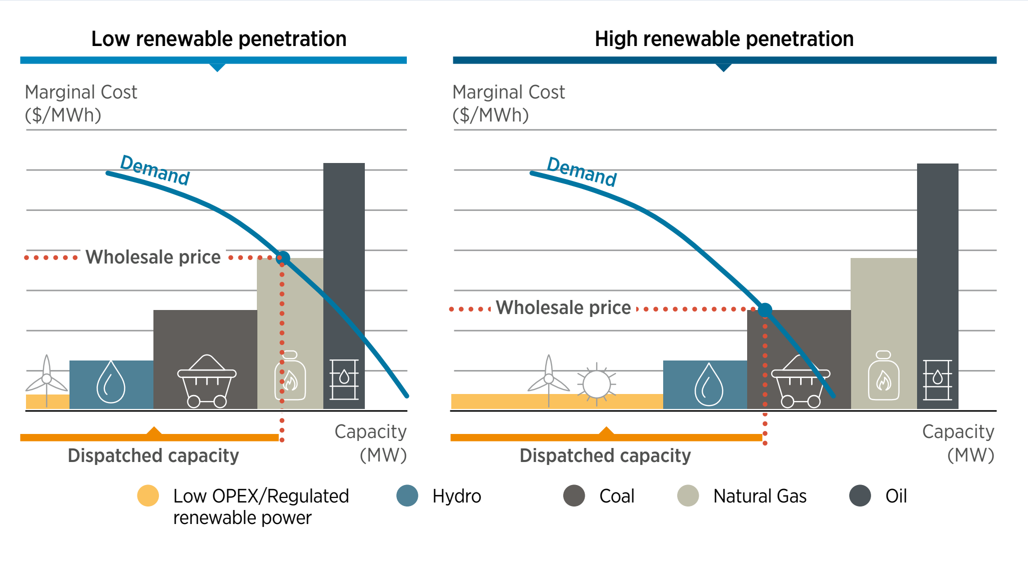
Understanding misalignments requires simultaneously considering the concepts of cost, price and value, as well as their alignments or lack thereof. The ultimate role of the organisational structure is setting up pricing mechanisms that allow cost recovery while reflecting the value of the power system and fostering social value creation.

Pricing mechanisms deal with part of the challenge and are complemented by additional pricing components such as subsidies and regulated payments. The cost and price dimensions often have hidden components (such as externalities) that may result in misalignments (IRENA, 2020d). The value dimension is the most often overlooked, while in fact it should be the powerhouse for socio-economic activity. It comprises both power system value and additional social value. Even for renewable energy technologies the contribution to the value dimension differs depending on how and where these technologies are developed, deployed and operated. Price minimisation is often adopted as the main or sole goal. However, minimising price is likely to produce significant misalignments.

The most known and discussed misalignment (see Figure 4.10) is that related to incumbent marginal pricing and the deployment of renewable generation (also known as cannibalisation effects or the missing money problem), although its wider implications for the energy transition are still not being properly addressed. Indeed, today's prevalent marginal-price-based organisational structures are misaligned with the requirements of generation technologies with low operating expenditure and limited dispatchability (and therefore low marginal costs), making them unfit for the renewable energy era. The increasing penetration of renewable energy generation with low marginal costs, under marginal pricing mechanisms, results in a compression of clearing prices. This has often been celebrated as good news, with the promise of dramatically lowering electricity prices for everyone as soon as support mechanisms for renewable energy are phased out. But this misses the point about the dynamics at play, since retiring support mechanisms would collapse the system operating under the current organisational structure. In life-cycle terms, the total costs of providing renewable

The ultimate role of the organisational structure is setting up pricing mechanisms that allow cost recovery while reflecting the value of the power system and fostering social value creation.

FIGURE 4.10 Misalignments in marginal pricing allocation mechanisms: Missing money and cannibalisation effects



Note: OPEX = operating expenditure; MW = megawatt; MWh = megawatt hour.

electricity are lower than for fossil fuels, but in the absence of the right organisational structure these potential benefits cannot be materialised. Given the high ratio of capital expenditure to operating expenditure in the renewable energy generation cost structure, the almost unlimited compression of clearing prices brought about by renewable energy deployment under marginal pricing mechanisms is a recipe for failure. The more renewable energy enters the system, the lower its remuneration becomes, reducing prospects for cost recovery and paralysing new investments, even when renewable energy is completely cost competitive. Moreover, the deployment of renewable energy under this paradigm is unlikely to properly address the value dimension, with the deployed renewable energy capacity not contributing to social value creation as much as it could and not even adequately contributing to power system value. Effects from this misalignment ripple out beyond renewable energy generation to affect the needed flexibility mechanisms being procured under the same marginal pricing mechanism. Hence, an organisational structure based on marginal pricing cannot support a power system based on renewable energy generation.

The way forward

The time has come for a new power system organisational structure that can support the energy transition and the power systems of the future. Until now, efforts to encourage this evolution have involved adjustments to current power system structures, which have contributed to some of the misalignments. Without a more comprehensive rethinking of power system structures, those misalignments will create barriers that could delay or even endanger the energy transition.

The good news is that instruments that have proved capable to support the energy transition, if properly integrated, are already available: power purchase agreements have proven suitable for supporting the deployment of capital-intensive renewable power plants, minimising the cost of procuring renewable power by keeping finance costs low. Wholesale markets featuring temporal and spatial granularity have proven able to elicit investments in flexible resources.

The "dual procurement" approach takes into consideration these experiences and integrates them into a holistic vision of how a power system's structure could be made fit for the transition. In the dual procurement approach, the procurement of electricity is divided into two complementary mechanisms, each one fit for the product it procures: long-term renewable energy (LT-RE) procurement and short-term flexibility (ST-flex) procurement. Auctions or public ownership become the backbone of the LT-RE, through long-term procurement mechanisms that address the requirements of capital-intensive technologies. The ST-Flex addresses the procurement of flexible resources needed for the reliable operation of a renewable-energy-based power system, and is based on marginal prices, with a granular bidding format and without scarcity price caps that could limit the economic feasibility of investments in flexibility. Essential characteristics of the two procurement mechanisms are described in Table 4.5.

Without a rethinking of power system structures, misalignments will create barriers that could delay or even endanger the energy transition.

TABLE 4.5 Overview of policies to support energy transition solutions

LT-RE PROCUREMENT	ST-FLEX PROCUREMENT
Based on **periodic long-term product-based allocation** mechanisms (auctions, direct public investment...)	Based on the **short-term dimension of current dispatch** mechanisms (balancing markets, regulated dispatch, ...)
Procures **renewable electricity** (VRE and dispatchable RE) and enables **RE supply adequacy** with the adequate anticipation	Procures **flexibility** (DSM, DER, storage, dispatchable RE, P2X, V2G, ...) and enables **flexibility supply adequacy**
Designed to **match supply and demand** as much as possible **on the long-term** (capturing temporal and locational value to the power system)	**Matching supply and demand on the short and very short term** (capturing temporal and locational value to the power system)
Driven by long-term load forecast within integrated energy planning	Driven by the short- and very short-term deviations between the scheduled load/REs production and real demand/production
Provides a safe investment environment that minimises finance costs for CAPEX-intensive technologies	**Liberalised systems:** allowing prices to vary from very high to low and even negative. Additional regulated payments if needed (especially during the transition period: LT-Flex) **Regulated systems:** enabling framework for deploying and operating the required flexibility capacity
The dual procurement **economic signals should reach the retail rates** (or prices) of all users to promote their participation in system operation, while simultaneously addressing distributional issues so that collaborative engagement is achieved in a just transition.	
Socially-wide collaborative governance (public or private): Enabling effective social and users participation in planning and operation, fostering the required collaborative framework for social value creation	

Source: IRENA, forthcoming-d.

Note: CAPEX = capital expenditure; DER = distributed energy resources; DSM = demand-side management; LT-Flex = long-term flexibility; LT-RE = long-term renewable energy; P2X = Power-to-X; RE = renewable energy; ST-flex = short-term flexibility; V2G = vehicle to grid; VRE = variable renewable energy

4.2.2 Increase energy conservation and efficiency

As noted in Chapter 2, energy conservation and efficiency will deliver around a quarter of the emissions reductions needed in the energy sector under the 1.5°C Pathway. Energy efficiency includes measures related to reducing demand and improving efficiency across industry, buildings and transport sectors.

Increase energy conservation and efficiency in heating and cooling

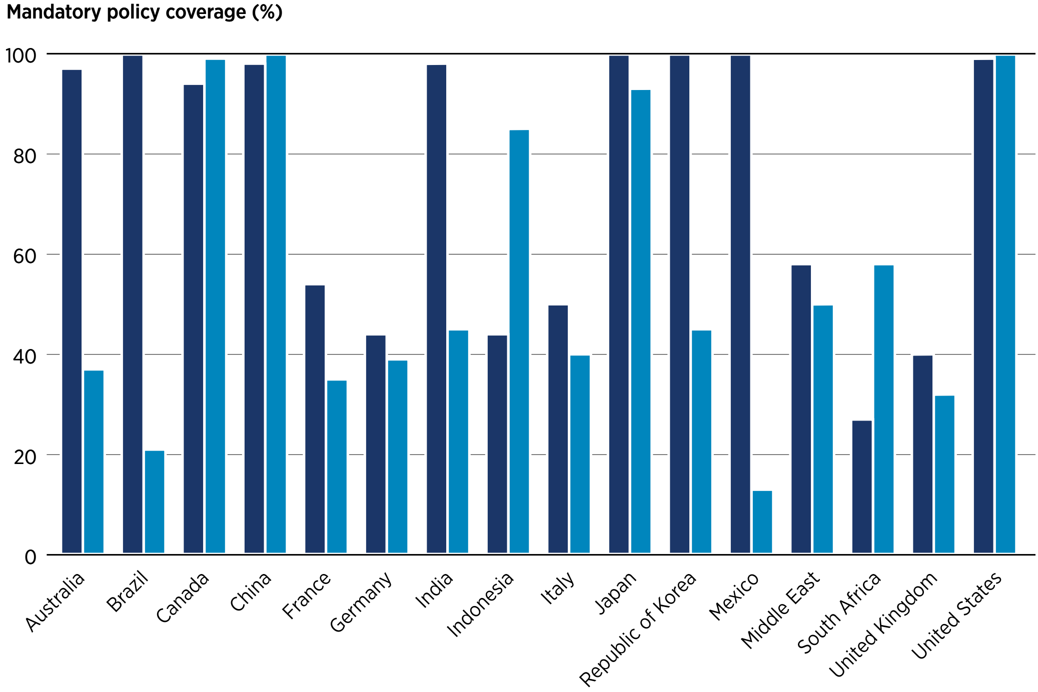
Critical for the energy transition in buildings and industrial processes are energy efficiency policies such as building codes, support for building retrofits, labelling policies and appliance standards. Most are cost efficient in the medium term and can improve the cost competitiveness of renewable heating and cooling applications. It is, however, important to address prevailing challenges associated with ownership structures, equitable access and benefits sharing of energy efficiency investments and policies, as well as potentially extended payback periods. Campaigns to raise the awareness of end users also play an important role in the adoption of energy efficiency measures. This section discusses a portfolio of policy measures to accelerate the adoption of energy efficiency measures across sectors.

Minimum Energy Performance Standards

Minimum Energy Performance Standards (MEPS) could support industrial, commercial and residential users to procure and switch to more energy-efficient appliances or equipment such as electric heating and cooling technologies. MEPS have been widely used by countries to regulate the cooling appliance market, covering more than 80% of space-cooling appliances in the commercial sector and 65% for residential uses. In the United States, China, Canada and Japan, almost all the space-cooling activities need to meet the mandatory MEPS (see Figure 4.11) (IRENA, IEA and REN21, 2020). However, the MEPS need to be adjusted according to technology and market conditions to ensure that mandates are optimally set.

Energy efficiency policies are critical for the energy transition.

FIGURE 4.11 Global energy use for space cooling covered by MEPS in selected juristictions, 2018



Source: IRENA, IEA and REN21, 2020.

In Australia and New Zealand, the Energy Label Policy (since 1987) and MEPS (since 2004), as the major pillars of the Equipment Energy Efficiency (E3) Programme, have significantly improved the efficiency performance of space-cooling equipment in the market. In 2018, Australia amended the energy labelling policy to cover more technologies and revised the efficiency metrics. New regulation also requires labelling the demand-response capacity which could be aggregated and provide system flexibility. Japan's Top Runner Programme provides another successful example. It targets energy-intensive equipment, which is regulated by a set of energy efficiency standards and targets. The Top Runner Programme labels the most energy-efficient products on the market to encourage competition among manufacturers. This is complemented by disclosing and fining companies that are failing to achieve the energy efficiency targets (IRENA, IEA and REN21, 2020).

Building codes

Building codes represent a set of regulations and requirements introduced by national or sub-national governments to guide buildings' construction, operation, renovation and repair activities. Building codes can be mandatory or voluntary and may cover only new buildings or also existing buildings and structures. The building codes can set requirements for the energy efficiency of buildings by specifying insulation standards and therefore reduce the heating and cooling needs. They can also set greenhouse gas emission targets and parameters for carbon footprints. In 2019, only 41 countries had building codes in place to mandate energy efficiency and renewable energy.

In France, the building codes include requirements for the carbon intensity of buildings' heat supply. In Scandinavian countries, building codes are widely adopted to set energy efficiency standards and encourage renewable heat. In Finland, the carbon intensity of heating is required by building codes. Sub-national governments including municipalities could play pioneering roles by adopting ambitious targets and standards in local building codes and related policies. The member cities of the Global Covenant of Mayors for Climate & Energy have committed to adopt and improve local building codes to be more ambitious than national standards. The European Union has required all new buildings to be nearly zero-energy by 2021. Singapore has also set zero-energy standards for new and existing buildings.

Policies for building retrofitting and renovation

Building retrofitting and renovation could improve energy performance through improved insulation and structure, introducing more energy-efficient technologies (such as district heating and cooling) and other solutions. Policies to support retrofitting and renovation for reduced emissions and consumption could be included in the building codes, including financial incentives and standards for buildings' retrofitting, refurbishment and renovation.

Policies and measures for district heating and cooling

Investments are also needed to upgrade ageing district heating and cooling networks with low efficiency and high operating temperatures (designed initially for fossil-fuel-based heat), which are not compatible with many renewable technologies, and to develop new ones. In this context, financial incentives, fiscal measures and guarantees can offset the high capital costs and financial risks. Measures include subsidies, grants or energy-related tax incentives for private-sector utility providers based on decarbonisation impacts. Debt guarantees to minimise risks for potential investors and concessional finance from multilateral development banks may be needed where it is difficult to secure financing locally or obtain interest-rate buydowns for more accessible finance (IRENA, 2017d). Kazakhstan is using development bank loans to refurbish its district heating systems and Denmark, Germany, Iceland, Norway and Sweden all offer financial incentives for investment in district heating and cooling infrastructure (IRENA, IEA and REN21, 2020). The Canton of Sarajevo (Bosnia and Herzegovina) developed a feasibility study for the improvement and decarbonisation of its urban district heating network, with the co-operation of the Italian Ministry of Environment, Land and Sea Protection and the United Nations Development Programme (IRENA, 2019e).

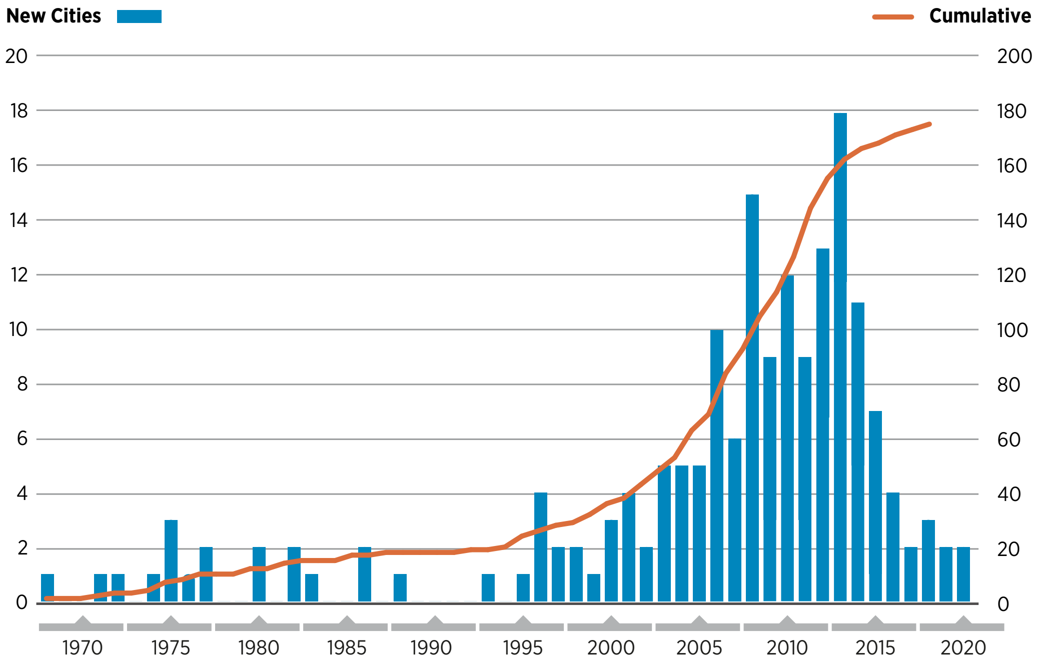
Increase energy conservation in transport

Policies for a modal shift in urban transport

Decarbonising the transport sector, among other measures, requires a shift from energy-intensive to low-carbon modes. A modal shift could significantly improve the energy efficiency of transport, especially in the urban context. This could be achieved by promoting energy-efficient mobility modes (*e.g.*, public transit, rail-based transit systems, car sharing) including non-motorised ones such as cycling and walking. Public transit and non-motorised mobility are complementary and work well together. A growing number of cities are introducing bus rapid transit (BRT) systems (Figure 4.12). Public campaigns are often undertaken by local governments to encourage green mobility modes. For example, Vancouver (Canada) launched a city campaign to encourage cycling and reduce private car use. Other polices, such as preferred parking fees, highway tolls and dedicated driving lanes for shared driving and public transit, could encourage the shift from private ownership to public transit.

Public transportation fleets also offer the opportunity to utilise renewable fuels. For instance, many cities in emerging countries, such as China and India, are promoting electric buses. Santiago (Chile) had 800 electric buses out of a total bus fleet of 6 700 buses by the end of 2020. In Europe, Oslo (Norway) and Gothenburg (Sweden) are operating fleets of electric buses.

FIGURE 4.12 Cities with bus rapid transit systems, per year and cumulative, 1968–2020



Source: IRENA, 2021e.

Policies to avoid and reduce transport needs

Structural changes and behavioural policies in the transport sector can have a multi-faceted effect by promoting the use of public transportation and other mobility services, and also reducing avoidable travel through improved planning (*e.g.*, transit-oriented development) and activity pattern changes (*e.g.*, promotion of remote working). A reduction in traffic volume further reduces the demand for renewable fuels including biofuels and electricity for charging electric vehicles.

Well-designed land use policies can significantly reduce or even eliminate unnecessary transport needs, for instance, by improving access to the cities' commercial districts. Transit-oriented development in the urban context maximises the residential and business centres within range of public transport and walking distance. In this way, most commercial activities could rely on public transit and reduce the use of private cars. Policies to encourage mixed urban development, with housing, commercial outlets, institutions and entertainment activities together in a specific urban area, can make new developments more sustainable from a transport needs perspective. In dense cities with high numbers of residents and jobs per square kilometre, travel distances would be shortened.

Encouraging new activity patterns can be achieved through, for instance, telecommuting and e-learning. While recognising that this may not be an option for a significant share of the workforce, telecommuting allows employees to work at home, or from a remote location for all or part of their workweek. In 2019, the city of San Antonio (United States) included telecommuting in its strategy to reduce car trips and related air pollution. Following the outbreak of the COVID-19 pandemic in early 2020, many employers permitted or even required office workers to work remotely, giving an unplanned and involuntary boost to forms of telecommuting enabled by video conferencing software. Although it is too early to judge how entrenched such forms of work will become in the long run, expectations are that the role of centralised offices has been altered fundamentally (IRENA, 2021e).

Structural changes and behavioural policies are needed to reduce avoidable travel through improved planning and activity pattern changes, while promoting the use of public transportation.

4.2.3 Electrify end-use sectors

Electrification of end uses represents an important pillar of the energy transition. Targets for renewable power should consider the rising demand from the electrification of end uses, in line with long-term decarbonisation objectives. Policies and measures are needed to support the electrification of heating and cooling and transport, and also to support electrification in achieving its potential for providing system flexibility.

Electrification of heating and cooling

For heating and cooling, heat pumps are two to four times more efficient than conventional heating systems. Their uptake has been supported mostly through fiscal and financial incentives. Denmark, for instance, reduced the tax paid on electricity-based heat as part of the country's plan to be fossil fuel free by 2050 (McLaughlin, 2019). Germany's Market Incentive Programme has dedicated around USD 360 million per year in grants and loans for small-scale renewable heat systems like heat pumps. China provided government subsidies equal to around 10% of the retail price of heat pumps, depending on their rated heating capacity and efficiency.

Electrification of transport

In the transport sector, the adoption of electric vehicles continues to grow aided by enabling policies. Targets for electric vehicles are increasingly being adopted at the national and sub-national levels. Costa Rica, for instance, is targeting 100% of vehicle sales to be zero emission by 2050 and Japan aims to have all cars be electric by 2050 (SLoCAT, 2020). On a sub-national level, Shenzhen (China) aims for 60% of new registered vehicles to be electric from 2021 to 2025 and to deploy 1 million electric vehicles by 2025 (Shenzhen DRC, 2021).

Financial incentives are often provided to support the uptake of electric vehicles. Germany has recently doubled the bonus provided to buyers of electric cars to EUR 3 000, and EUR 2 250 for hybrids costing less than EUR 40 000. The bonus for electric vehicles will be lowered in two steps until 2025 and that for hybrids could be removed altogether from 2022 (Reuters, 2020). In fact, support policies for transition-related technologies are often temporary, ending when these technologies achieve price parity and further evolve to ensure deployment at levels consistent with broader energy transition ambitions.

Norway, the world leader in electric vehicles, incentivises their deployment by offering exemptions from registration tax and value-added tax (EAFO, 2021), among other policy instruments. An alternate approach also followed is to tax vehicles according to their emissions. In the United States, buyers of electric cars receive a federal tax credit of up to USD 7 500 for the first 200 000 units sold by each manufacturer (United States DoE, n.d.). As discussed further in Section 4.4, financial incentives, such as tax credits, to facilitate adoption must also consider aspects related to equity, i.e., support is accessible to, and benefits, all end users in a just manner.

The electrification of transport also requires significant investments in enabling infrastructure, particularly for charging. With electric vehicles accounting for more than 80% of all road transport activity by 2050, their market entry will be contingent upon co-ordinated investments in charging infrastructure and power grids. Smart charging solutions can significantly facilitate the integration of variable renewable energy by leveraging storage capacity and the flexibility potential of the demand side (IRENA, 2019e). Heavy vehicles such as long-haul freight trucks, marine ships and airplanes that are unlikely to be fully electrified will require investments in infrastructure to deliver renewable solutions such as biofuels and green hydrogen-based fuels.

Electrification as a source of flexibility

Heat pumps and electric vehicles have the potential to become sources of system flexibility, facilitating the integration of larger shares of variable renewable energy. Exploiting the potential will require proactive policies for the upgrade of power networks, supported by digital technologies for monitoring and controlling the consumption profiles, as well as an increasing participation of new stakeholders such as aggregators of demand and distributed resources. As discussed in the In focus section, power systems' organisational structures need to be redesigned to support the integration of greater shares of variable renewable energy, for example, by removing barriers to the participation of renewables in ancillary services markets.

Moreover, electricity tariff structures need to be redesigned to meet the growing need for flexibility. Demand-side flexibility can be increased through time-of-use tariffs and other smart rate-setting options, thus facilitating the system-friendly integration of additional loads from heating and cooling and transport. Policies can also enable new actors and business models that bring flexibility services.

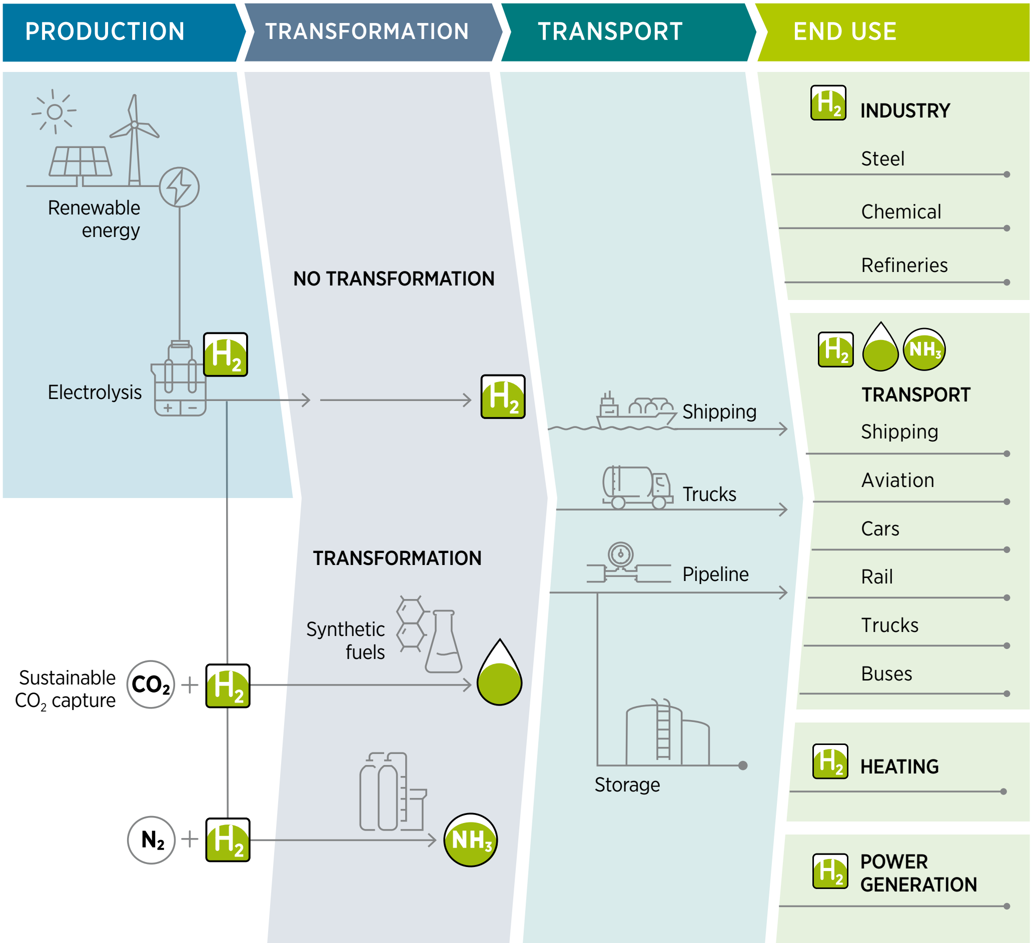
Finally, forward-looking plans should be developed to integrate the additional renewable electricity and address the load imposed by the electrification of end uses through grid expansion and strengthening. In fact, sector coupling with the direct and indirect electrification of end uses (*e.g.*, through green hydrogen) offers opportunities to enhance the flexibility of the energy system facilitating integration of larger shares of renewables.

4.2.4 Support the development of green hydrogen

In recognition of the important role green hydrogen will play in advancing the energy transition, several countries have introduced dedicated policies to support adoption. By 2019, 15 countries and the European Union had implemented green hydrogen policies, about two-thirds focusing on the transport sector (IRENA, 2020l). Transport is, however, only one target end-use sector for the hydrogen value chain (Figure 4.13).

Demand-side flexibility can be increased through time-of-use tariffs and other smart rate-setting options, to accommodate for additional loads from heating and cooling and transport.

FIGURE 4.13 Green hydrogen value chain



Note: CO_2 = carbon dioxide; H_2 = molecular hydrogen; N_2 = dinitrogen; NH_3 = ammonia.

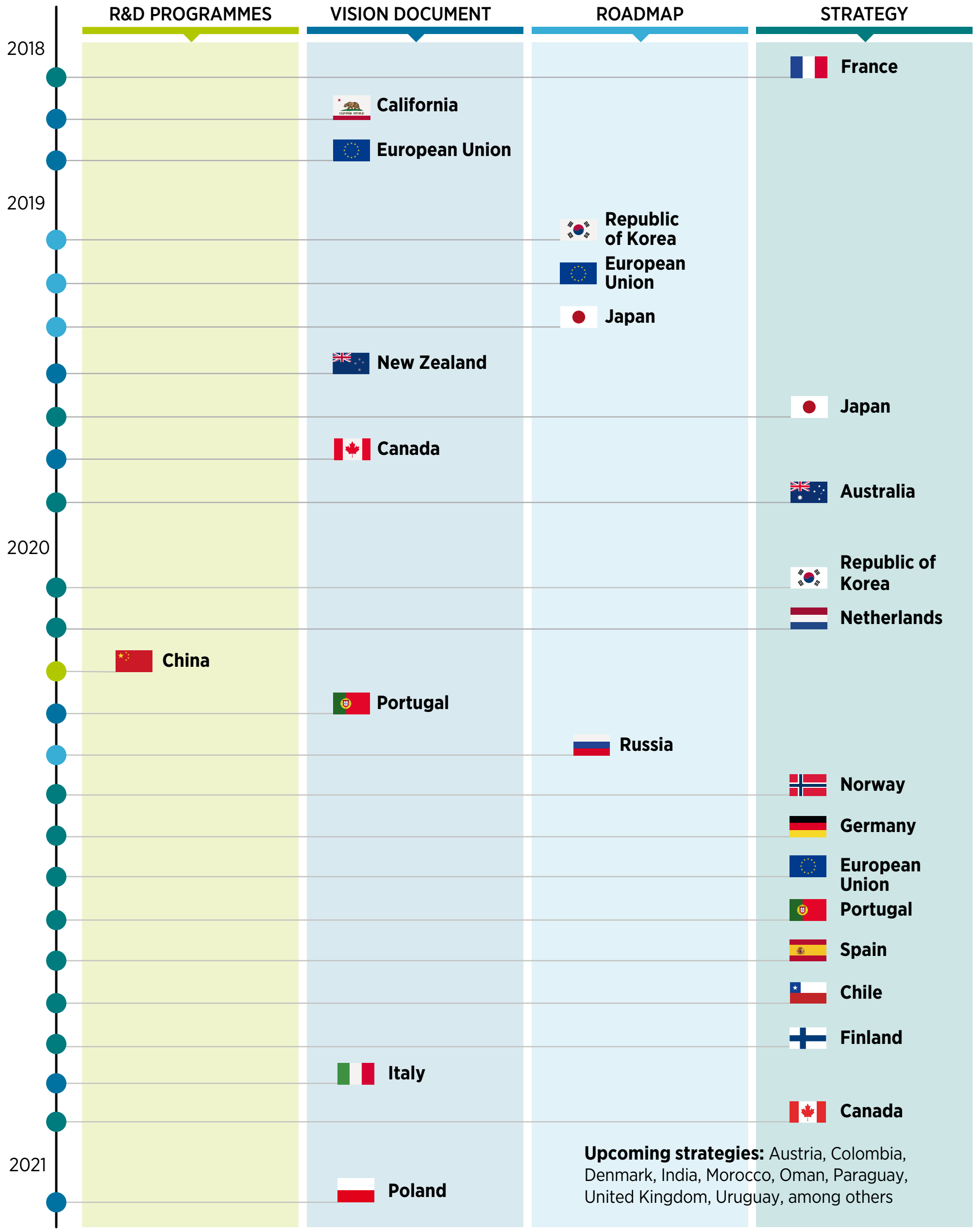
Each part of the hydrogen value chain – including electrolysis, transport, storage, conversion in other energy carriers and feedstocks (ammonia, methanol, synthetic fuels) and end uses – necessitates support to scale up to the level needed for the energy transition. The installed capacity of electrolysers needs to be raised from 200 MW today to 5 TW installed by 2050 in order to produce the 400 Mt.

This calls for policy action, with dedicated measures for each part of the value chain. Given the fact that green hydrogen touches many different parts of the energy sector, an enabling policy framework should consider the following four key pillars, as identified in IRENA (2020l).

- **National green hydrogen strategy:** This defines the level of ambition for hydrogen across end-use sectors and the support required and provisioned for. A national hydrogen strategy can serve as a reference point for attracting the private sector and investments. A growing number of countries are adopting national hydrogen strategies to position themselves in a sector that is gaining traction. Hydrogen strategies typically are preceded by vision documents and roadmaps. Figure 4.14 illustrates government hydrogen-related initiatives announced between June 2018 and February 2021. The strategy development phase also offers the opportunity to engage civil society through open consultations and in setting priorities.

Each part of the green hydrogen value chain needs support to scale up to the level needed for the energy transition.

FIGURE 4.14 Government hydrogen-related initiatives announced between June 2018 and February 2021



Based on IRENA, 2020l.

Note: R&D = research and development.

- **Priority setting:** Green hydrogen can be utilised in a wide range of end uses. In order to avoid diluting efforts, policy makers are encouraged to consider three key principles when selecting priority end uses to be developed:

  First, despite the great promise of green hydrogen and its suitability to replace fossil gases, it is not a complete substitute for fossil fuels. Instead, it is just one of several possible decarbonisation alternatives that should be carefully weighed when setting priorities.

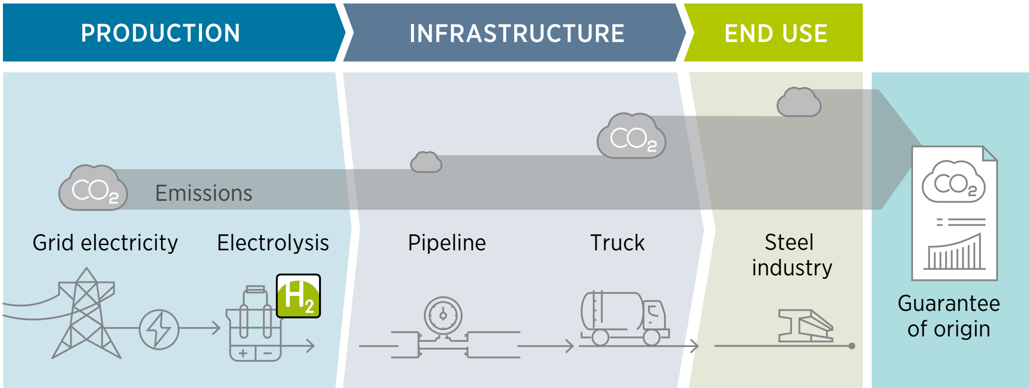
  Second, policy decisions should include what applications should be prioritised and how quickly to make the shift from fossil fuels to green hydrogen. Policy makers should identify the highest-value applications for a given amount of green hydrogen, in order to focus their efforts where they could provide the most immediate advantages and enable economies of scale.

  Finally, the principle of additionality is crucial for the renewable energy used for green hydrogen production. In other words, if there are other productive uses for the electricity being generated from renewable sources, that electricity should not be diverted from those uses to produce green hydrogen. Instead, green hydrogen should be produced only from additional renewable energy capacity that would not otherwise be commissioned and electricity that would not otherwise be consumed.

- **Guarantees of origin:** Since the molecules of green hydrogen are identical to those of grey hydrogen, a certification system – referred to as "guarantee of origin" (GO) – is needed to track the origin and to account for the life-cycle emissions of hydrogen (Figure 4.15). To be useful for producers, policy makers and end users, GO schemes should provide a label for the hydrogen product that clearly indicates its "shade". GO schemes will be a key element of a green hydrogen system, at least until carbon-intensive hydrogen is no longer produced.

Green hydrogen is just one of several possible decarbonisation alternatives that should be carefully weighed when setting priorities.

FIGURE 4.15 Guarantees of origin and life-cycle emissions



Note: CO_2 = carbon dioxide.

- **Enabling policies:** The final pillar is the adoption of enabling policies and measures to create the socio-economic space that would allow green hydrogen to become a part of the energy system (see also Section 4.1). Economywide policies that affect the sustainability and pace of the transition can create the ecosystem for green hydrogen to develop industrial, economic and social value, including jobs. Examples of such measures are those that maintain industrial competitiveness and create export opportunities and the identification and leveraging of economic growth and job creation opportunities. Another important cross-cutting action is the collection of statistics. Hydrogen is not currently included in national energy balances, because it is considered a chemical product. Including hydrogen supply and demand as a separate category in national energy balances (similar to electricity, fossil fuels or bioenergy) allows better identification of energy flows and provides a solid basis for further analysis. Maintaining a central repository of data on hydrogen deployment across different sectors (such as megawatts of electrolysis or number of fuel cell electric vehicles) can make market information (such as prices, traded volumes and share of green and low-carbon hydrogen) openly available to promote transparency. This action will require international co-operation to align methodologies and ensure mutual comprehension.

These policy pillars represent the framework necessary for green hydrogen policy making. In addition, some of the barriers faced by the green hydrogen sector must be tackled with dedicated measures, focused on specific parts of the value chain, for example, the supply side (see Box 4.7). Policies will also be needed to support adoption of hydrogen-based solutions on the demand side, in particular in the industrial and long-haul transport sectors.

BOX 4.8 Policies supporting the supply of green hydrogen

In any energy system, policies can support the demand side, by supporting or mandating the adoption of renewable energy solutions by consumers, or the supply side, by supporting the production and transportation of clean energy or clean energy carriers. In the power sector, supply-side policies were generally preferred and policy support for green hydrogen could draw on the experiences from the power sector with appropriate adaptations.

Policy makers can set targets for the growth of electrolyser capacity and provide support for each stage of deployment, supporting electrolysers and electrolyser manufacturing capacity and ensuring a sufficient supply of renewable electricity. There are a wide range of possible support schemes, including direct grants, feed-in tariffs and premiums, tax incentives and funding for research and development. Regulation and planning will also play an important role. A more detailed analysis is available in IRENA (2021i).

Regarding infrastructure, it is important to standardise the regulation of hydrogen infrastructure in line with international best practice, plan infrastructure step by step (prioritising industrial demand) and assist gas transmission system operators by financing the infrastructure to store and transport hydrogen.

Source: IRENA, 2021i.

4.2.5 Ensure the sustainable use of bioenergy

Sustainable bioenergy is an important technology for the energy transition and its greater use will play a significant role to meet decarbonisation objectives across power, heating/cooling and transport end-use sectors. As noted in Chapter 2, in IRENA's 1.5°C Pathway, bioenergy will be needed to provide heat in industrial processes, cooking and space and water heating in buildings and fuels for transport. It will also be needed as feedstock in the petrochemical industry to produce chemicals and plastics. The energy transition will also involve phasing out the traditional use of bioenergy and replacing it with a combination of modern fuels, including biogas.

Policies to support sustainable bioenergy adoption across the power and end-use sectors were discussed in Section 4.2.1 along with other renewable energy technologies. Broadly, an enabling policy framework for sustainable bioenergy must consider aspects related to a clear long-term strategy, financing support, market access, support for innovation, enabling measures and sustainability governance. This section will specifically discuss the sustainability governance aspect which is critical to ensure the strongest compliance to standards relating to social, economic and environmental impacts. Box 4.8 discusses policies and measures to ensure the sustainable use of bioenergy.

BOX 4.9 Policies and measures for the sustainable use of bioenergy

The transition to renewables addresses many of the challenges posed by incumbent energy technologies at the intersection of society and the planet (*e.g.*, climate change, local air pollution). However, even with a renewables-based energy system there is potential for negative environmental and social impacts if they are not adequately factored into the transition process and its policies.

Among the main sustainability concerns are those that relate to bioenergy production and consumption. Some of these concerns relate to environmental aspects, including greenhouse gas emissions related to direct or indirect land-use change, impacts on air and water quality and biodiversity, among others.

Comprehensive guidelines and tools are needed to support policy makers in defining rules for sustainable biomass. The Food and Agriculture Organization of the United Nations has developed such guidelines. Another international platform, the Global Bioenergy Partnership, has also produced a set of indicators, including those to assess environmental impacts, to help stakeholders better understand ways to ensure the sustainability of bioenergy.

Government legislation and independent voluntary certification schemes can also be introduced to demonstrate the sustainable practice of bioenergy industries. For example, the EU's Renewable Energy Directive to 2030 introduces enhanced sustainability criteria for bioenergy production. It excludes biofuels based on raw materials produced on land with high carbon stocks or large effects on biodiversity, and requires minimum greenhouse gas savings for bioenergy production. Some independent certificate schemes such as the Forest Stewardship Council and Sustainable Forestry Initiative are also widely recognised by related industry players to demonstrate sustainable bioenergy practices and reduce the negative impacts of bioenergy production on the planet (IRENA, forthcoming-b).

The energy transition's planning should prioritise the use of bioenergy for those applications that do not have other renewable-based alternatives (this would rule out the use of bio energy for low-temperature applications like heating buildings or producing domestic hot water, for example), and accelerate the development of alternatives for hard-to-abate sectors, like hydrogen and hydrogen-based synthetic fuels, so that the use of biomass is reduced as much as possible and can be secured from sustainable sources.

4.3 POLICIES FOR STRUCTURAL CHANGE AND A JUST TRANSITION

The transition under the 1.5°C Pathway will influence how we consume, produce, travel and commute, and thus transform global, regional and local economies. Chapter 5 goes deeper into estimates of the impact of the transition on global economic growth, employment and welfare. Even as, globally, the benefits are large, impacts vary across regions and countries that feature markedly different contexts and challenges. If misalignments are not well managed through targeted policies, inequitable outcomes could result. This section discusses a portfolio of policies related to structural change and just transition (summarised in Table 4.6).

Even as globally the benefits of the energy transition are large, impacts vary across regions and countries that feature markedly different contexts and challenges. If misalignments are not well managed through targeted policies, inequitable outcomes could result.

TABLE 4.6 Overview of structural change and just transition policies

OBJECTIVE	EXAMPLES OF MEASURES	COMMENTS
Address potential misalignments in labour markets	Scotland's "Transition Training Fund" offers grants for the retraining of oil and gas workers.	Ensuring a just and fair transition will require an in-depth understanding of how structural changes will affect labour markets as well as measures to mitigate negative impacts and foster benefits.
Develop local value chains	India has launched a Production Linked Incentive scheme to promote manufacturing of high-efficiency solar photovoltaic (PV) modules and to reduce import dependency.	Enhancing and leveraging domestic capabilities requires carefully crafted incentives and rules, business incubation initiatives, supplier-development programmes, support for small and medium enterprises and promotion of key industrial clusters.
Provide education and build capacity	The Ethiopian Electric Utility plans to increase opportunities for women in the electricity sector.	Early exposure to renewable-energy-related topics and careers is vital for sparking young people's interests in pursuing a career in the sector, and also to increase social acceptance by a knowledgeable citizenry.
Support a circular economy	The European Waste Electrical and Electronic Equipment Directive sets ambitious rules and regulations for recycling solar PV panels.	Policies and measures are needed to ensure the sustainability of energy transition-related solutions and their smooth integration in existing ecosystems in terms of sustainability, circular economy principles and reduced environmental impacts.
Support community and citizen engagement	Countries such as Germany, Denmark and Japan encourage direct citizen participation in renewable energy projects.	Community energy can play an important role in accelerating renewables deployment while generating local socio-economic benefits and increasing public support for local energy transitions.

Ensuring a just and fair transition will require an in-depth understanding of how structural changes will affect different areas and populations as well as measures to mitigate impacts and foster benefits.

4.3.1 Address potential misalignments in labour markets

Economic structures and labour market policies are intricately intertwined. The challenges lie in reducing the dominance of fossil fuels (reflected in institutional fabrics, sectoral structures and investment priorities); altering patterns of commodity, technological and trade dependence and strengthening the supply chain structures necessary for supporting the energy transition. Ensuring a just and fair transition will require an in-depth understanding of how structural changes will affect different areas and populations as well as measures to mitigate impacts and foster benefits.

Labour market interventions could encompass adequate employment services (matching jobs with qualified applicants; promoting employee well-being; facilitating on- and off-job training and implementing job safety nets), along with **measures to facilitate labour mobility**, such as relocation grants. Facilitating collaboration between industry and educational institutions will also contribute to more co-ordinated skill-matching efforts. The future and the present labour force may not always be properly aligned (IRENA, 2019h), the main challenges being:

- **Temporal misalignments:** Job losses and gains will likely take place at different points in time rather than in parallel.
- **Spatial misalignments:** New jobs may be created in different communities, regions or countries than those where the principal job losses occur.
- **Educational misalignments:** Although retraining efforts can help to some extent, the skills associated with vanishing jobs do not necessarily match the profiles and occupational patterns required in emerging and growing industries.
- **Sectoral misalignments:** The relative changes in employment across economic sectors may vary, hence requiring a migration of labour force from some economic sectors to others. Rising industries may draw more heavily on raw materials or intermediate inputs from sectors that are quite different from those that supply declining industries. The indirect effects will thus vary.

In parallel to targeting young people for new careers in the renewable energy sector, the existing workforce also presents a potential talent pool, besides the justice considerations of not leaving them behind. **Reskilling and upskilling** measures will be vital for extending the employment benefits of the transition along the value chain and in the wider economy to workers.

Skills synergies between the offshore wind and oil and gas industries can be utilised, such as expertise in surveying and offshore installation; design and manufacturing of support structures; large-scale installation and operation and maintenance of offshore assets. Similarly, coal sector workers can also find new opportunities in renewables, and recent years have seen many instances of targeted recruiting of coal miners for work in the solar and wind sectors (Marston, 2018). For example, a United States-based study of synergies between coal and solar PV skills found that 43% of coal-fired power plant workers could be transitioned to the PV sector without additional training while in the coal mining industry 30–35% of jobs are specific to the industry and would require reskilling (Louie and Pearce, 2016). It is necessary to ensure that vulnerable workers and their communities do not shoulder an unfairly large burden due to the energy transition. Related efforts include measures to support income stability through unemployment insurance and other programmes, policy incentives for employers to retain (and retrain) workers where possible and flexible, longer-term employment contracts to promote job stability. Proactive strategies designed to minimise socio-economic disruption may also encompass public investments and economic diversification measures for affected regions and communities.

In addition to the identification of transferable skills, governments will also need to dedicate funds to the reorientation and reskilling of the workforce. An example of this is the Scottish government's Transition Training Fund which offers grants for the retraining of oil and gas workers who have lost their jobs or are at risk of redundancy (Skills Development Scotland, 2019). Partnerships between governments, industry and trade unions will play an important role in facilitating the shift for workers and securing safety standards and social benefits.

Reskilling and upskilling measures will be vital for extending the employment benefits of the transition along the value chain and in the wider economy to workers.

4.3.2 Develop local value chains

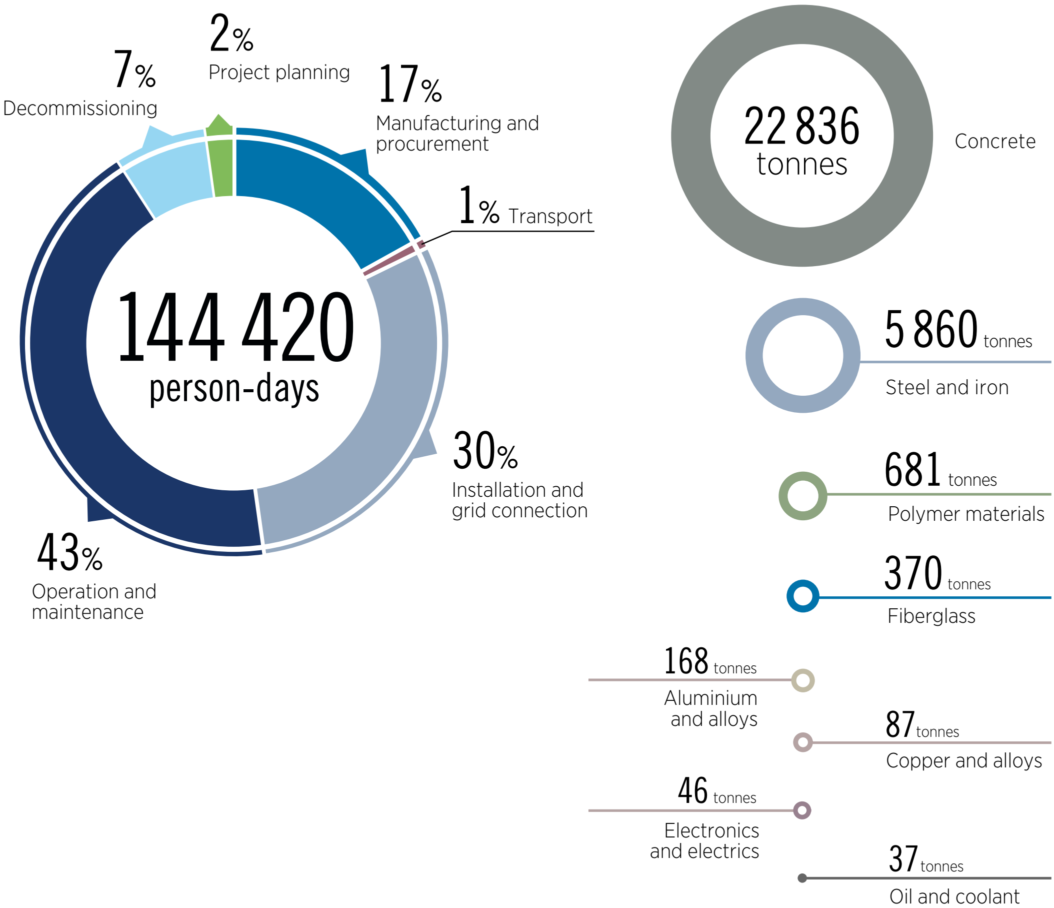
Bolstering efforts to strengthen local value chains will result in not only the creation of new renewable energy jobs but also the generation of income by leveraging existing and new economic activities. The current momentum for a green recovery offers a historic opportunity to pursue the ambitious measures that would lead to this much-needed structural change. These measures must be targeted towards all sectors and inputs along the value chain. The energy transition provides many opportunities for localisation and structural reform. Stocktaking of regional and local strengths is a pre-requisite, as well as analysing the potential of creating regional hubs for the manifold technologies necessary for the transition along a 1.5°C trajectory.

The use of industrial policy can support the development of internationally competitive local or regional suppliers, particularly in developing economies. Thus far, barriers to entry lie in the capital intensity of starting new production lines, or exclusive consolidation of supply chains. In India, for instance, a key feature of the recovery plan has been to encourage manufacturing across sectors such as solar PV, automobiles, textile, medical devices and electronics. A Production Linked Incentive scheme has been launched to promote manufacturing of high-efficiency solar PV modules and reduce import dependency. The incentive offered is designed to increase as the value addition grows (MNRE, 2021).

The availability of the materials and equipment, as well as skills, required along the value chain will also be an important factor in determining where local value creation can be maximised. For instance, as illustrated in Figure 4.16, a 50 MW wind farm would require 22 836 tonnes of concrete, 5 860 tonnes of steel and iron as well as other materials such as polymers, fibreglass and aluminium that are necessary for the local manufacture of components (IRENA, 2018d). This in turn would create 144 420 person-days of employment, primarily in operation and maintenance (43%) followed by installation and grid connection (30%).

Bolstering efforts to strengthen local value chains will result in not only the creation of new renewable energy jobs but also the generation of income by leveraging existing and new economic activities.

FIGURE 4.16 Distribution of material and human resource requirements for the development of a 50 MW wind farm



Source: IRENA, 2018d.

Quality assurance is key for a successful energy transition but should be turned into an entry point and not a barrier to the respective markets. Easy access to standardisation procedures, including training and skill formation (see Section 4.3.3), can reduce entry barriers for local firms seeking access to value chains. Promoting the shift to regional value chains will also foster global resilience to exogenous shocks, such as the interruptions seen during the COVID-19 pandemic.

Enhancing and leveraging domestic capabilities require carefully crafted incentives and rules, business incubation initiatives, supplier-development programmes, support for small and medium enterprises and promotion of key industrial clusters.

A key objective is to harness, enhance and leverage the capabilities of domestic companies (either home-grown firms or local subsidiaries of international companies) so they can support the energy transition. Suitable policies encompass initiatives and programmes to incubate new businesses and develop the capabilities of existing firms in the supply chain, with the help of low-cost loans or access to land, dedicated supplier capacity-building programmes and regional industrial clusters. Governments can take a direct role by:

- Designing renewable-energy-focused research and development strategies and ensuring uptake in the public and private sectors;
- Facilitating learning effects, spill-overs and technological transfers in renewables and energy efficiency through carefully designed incentives;
- Incentivising supply chain participation in renewable energy sectors by local firms, and actively supporting the creation of partnerships; and
- Establishing direct links to labour policy to translate targets and support measures into employment creation.

Small and medium enterprises play an important role in any attempt to maximise local benefits and diversify economies. It is important to incentivise small and medium enterprises, ease access to information, support the digitalisation of small firms and open up access to finance to support start-ups and, in the long run, innovation and economic opportunity. Start-ups benefit from the promotion of key industrial clusters, as do firms of any size along the value chain of a technology. The proximity of manufacturers, services and designers of a certain technology to a relevant market has additional benefits.

4.3.3 Provide education and build capacity

The renewable energy sector offers employment opportunities for people coming from a range of occupational profiles and backgrounds. Leveraging existing local capacities needs country-specific understanding of skill demand and supply, and of which relevant skills are readily available and which need to be developed or strengthened.

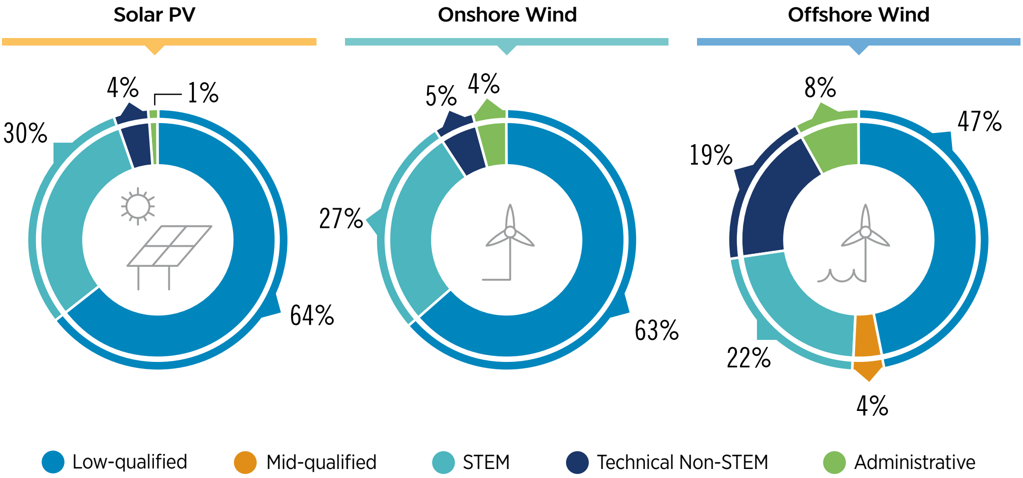
A thorough understanding of the jobs that will emerge domestically and the existing knowledge and skills that can be leveraged either from other industries or with skilling policies must go hand in hand with measures to increase renewable energy deployment.

The renewable energy sector offers employment prospects for people with a wide range of experiences and backgrounds, and many of the required skills are typically available in most countries. While there is a demand for professionals with training in fields such as science, technology, engineering and mathematics (STEM), as well as other highly qualified individuals (such as lawyers, logistics experts, marketing professionals, financial analysts and experts in regulation and standardisation), most jobs do not require a university degree, but high manual dexterity and on-the-job experience. The greatest demand from the renewable energy sector will be for factory workers, construction workers, technicians and tradespeople like plumbers and electricians. The low threshold of skills for many of these jobs opens doors to employment for many people, particularly where on-the-job training is available. Furthermore, some skill sets can be leveraged from other domestic industries, with some retraining.

Analysis of PV (IRENA, 2017e) and onshore wind industries (IRENA, 2018d) shows that a diverse set of jobs will be created, including jobs that require “lower” or less formalised skills. In fact, over 60% of jobs can be filled by people without university degrees (see Figure 4.17). Individuals with advanced STEM degrees represent around 30% (PV) and 27% (onshore wind) of the workforce, non-STEM professionals account for roughly 5%, while administrative personnel account for the smallest share (1.4%). A similar trend is seen in offshore wind where the largest share of employment (47%) is held by those with non-university skills and training.

A thorough understanding of the jobs that will emerge domestically and the existing knowledge and skills that can be leveraged either from other industries or with skilling policies must go hand in hand with measures to increase renewable energy deployment.

FIGURE 4.17 Human resource requirements in the solar PV and wind industries



Source: IRENA, 2017e, 2018a, 2018d, 2020b.

Note: PV = photovoltaic; STEM = science, technology, engineering and mathematics.

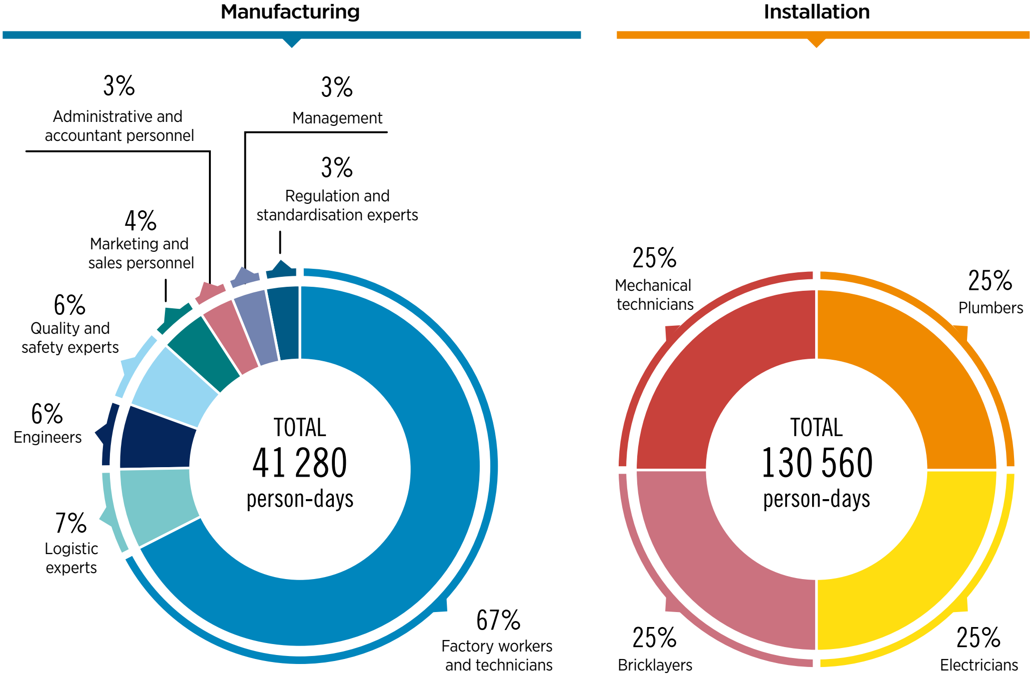
When it comes to the manufacturing of solar water heaters, as shown in Figure 4.18, 67% of the human resources required are for factory workers and technicians, and their installation also draws on several trades (plumbers, electricians, bricklayers, mechanical technicians) (IRENA, forthcoming -c).

Measures to safeguard the quality of renewable energy jobs are as necessary as those undertaken to increase their quantity. The notion of decent work encompasses many dimensions including fair income, workplace security, social protections, personal development prospects, freedom of organisation, equality of opportunities and equal treatment (ILO, n.d.-a). Given the diversity of the renewable energy sector in terms of industries, companies and supply chains, job quality and workplace practices can and do vary widely. National regulations, company policies and labour representation all play a vital role in areas such as wage levels and workplace protections. It is critical that workers and communities have a full voice in the decision making that drives the transition.

Realising the potential of the energy transition requires making use of all of the available talent pool as well as equitably distributing benefits. As such, targeted measures are required to train, recruit and retain women and other under-represented or marginalised groups (including older workers, ethnic and religious minorities, people with disabilities and those on a low income), and offer opportunities for career advancement.

Women, for instance, account for only 32% of the renewable energy workforce which, while higher than the 22% in the oil and gas industry, is still significantly less than their overall workforce participation (IRENA, 2019i). Also, parts of the renewable energy sector are far less open to women

FIGURE 4.18 Human resource requirements for the manufacturing and installation of solar water heaters



Source: IRENA, forthcoming-c.

than the average would suggest. This is true of the wind sector, where women represent only 21% of the workforce. When it comes to STEM-related roles the disparity widens further with women holding only 28% of STEM jobs across all renewables (14% in wind), compared to 45% of administrative roles (35% in wind) (IRENA, 2020m).

Ensuring the inclusion of under-represented groups requires a range of both educational and workplace measures. Early exposure to renewable energy careers, targeted scholarships and funded training opportunities, mentorships and apprenticeship schemes can all play a role in building the talent pipeline. In the workplace, attracting and retaining talent will require policies and practices that address the challenges faced by under-represented groups. For example, many women would benefit from policies that allow for work-life balance as well as equal opportunities for professional development (as shown in Box 4.9). People with disabilities, who make up an estimated 15% of the world's population (ILO, n.d.-b), may also benefit from workplace accommodations and adaptations. Such measures would often not only benefit the targeted group but also the workforce and society as a whole.

BOX 4.10 Fostering women's employment at the Ethiopian Electric Utility

The Ethiopian Electric Utility (EEU) is working towards increasing opportunities for women in the country's male-dominated electricity sector. As of late 2019, women represented only 19.2% of the EEU workforce and just 9% of managerial and leadership positions. To address this imbalance the EEU has set a target to increase this share to 30% women employees by 2023. To achieve this goal the EEU has built partnerships with the Ministry of Science and Higher Education and 12 universities to deliver science, technology, engineering and mathematics (STEM) courses. They are also offering scholarships to female staff for graduate studies and technical training. To increase the number of women in managerial positions, leadership training is also being developed. Targeted internships to female STEM graduate students have also been used to provide practical experience, with the opportunity for a permanent job if requirements are met. These efforts are being funded by an earmarked allocation for gender equity and citizen engagement within the budget of the Ethiopia Electrification Program.

Source: WRI, 2021.

Building a skilled energy transition workforce requires measures to both increase the talent pipeline as well as enhance the quality of education and training provisions.

Early exposure to renewable-energy-related topics and careers is vital for sparking young people's interests in pursuing a career in the sector, but also to increase social acceptance by a knowledgeable citizenry. The curriculums at higher education and vocational training institutions need to reflect the skills and competences needed under the energy transition. Certifications and national standards can play an important role in ensuring quality and performance. Professional and supplementary education and training are also important for upskilling the current workforce, ensuring that workers' skills evolve along with the demands of the sector. Targeted skill building is also needed in the energy access context (as shown in Box 4.10). In addition to strengthening the content of education and training programmes, it is also important to enhance the instructional methods used. For example, experiential learning methods by which students are encouraged to develop problem-solving strategies can help to prepare learners for jobs in the constantly evolving renewable energy sector where independent knowledge seeking will often be necessary.

Public-private partnerships can also play a crucial role in improving overall training quality while meeting sectoral labour requirements, promoting national skill standards and providing workplace training. In addition to training content, public-private partnerships can also play a role in the financing of training provisions through a shift from fees being the primary vehicle to a more integrated approach that incorporates multiple funding mechanisms including payroll-based training levies, tax incentives, scholarships and donations, vouchers and student loans (Dunbar, 2013).

BOX 4.11 Energy access skills

Building the skills necessary for scaling up the use of renewable energy is especially crucial in the energy access context. Projects shortlisted for the Ashden Award for Energy Access Skills feature a range of innovative solutions for addressing skills shortages (Ashden, 2021).

Sendea Academy in Uganda, which is made up of a collective of locally owned small and medium enterprises, aims to address skills shortages in the solar industry by providing training for technicians, entrepreneurs and sales, management and finance professionals (Sendea, 2021).

Other projects selected include the Bharatiya Bikas Trust in India which has provided professional development training to 14 000 bank workers to enable them to offer renewable energy loans; the Strathmore Energy Research Centre in Kenya which has developed innovative solar curricula; and the African Management Institute's Off-Grid Talent Initiative which trains companies and middle managers working in the off-grid sector.

4.3.4 Support a circular economy

Policies and measures are also needed to ensure the sustainability of energy transition-related solutions and their smooth integration within the planet and existing ecosystems, featuring circular economy principles and reduced environmental impacts. Potential impacts to mitigate include, for example, those on land and biodiversity in the case of bioenergy and large hydro, and on migratory species in the case of wind. Social and environmental impacts of mining activities and the use of relatively scarce components should also be considered and mitigated through provision for a circular economy including end-of-life management.

Together with industry and other stakeholders, governments need to prepare for the anticipated waste volumes of equipment – such as solar PV panels and batteries – by adopting eco-design requirements and **sustainable end-of-life management policies, including waste legislation** (Box 4.11). More data and analyses will be needed at the national level to support the establishment of suitable policy and regulatory frameworks. Information should be gathered through regular monitoring of amounts of waste produced by country and technology, the composition of waste streams, installed system performance and the causes and frequency of system failures. To further stimulate innovation in end-of-life management, research and development programmes across energy and waste sectors and industrial clusters can be effective. Tackling increasing waste streams will also lead to the expansion of existing waste management infrastructure, including regional markets in the absence of sufficient national waste volumes or country-specific technical know-how (IRENA and IEA-PVPS, 2016).

BOX 4.12 European Waste Electrical and Electronic Equipment Directive (WEEE) for end-of-life management of PV

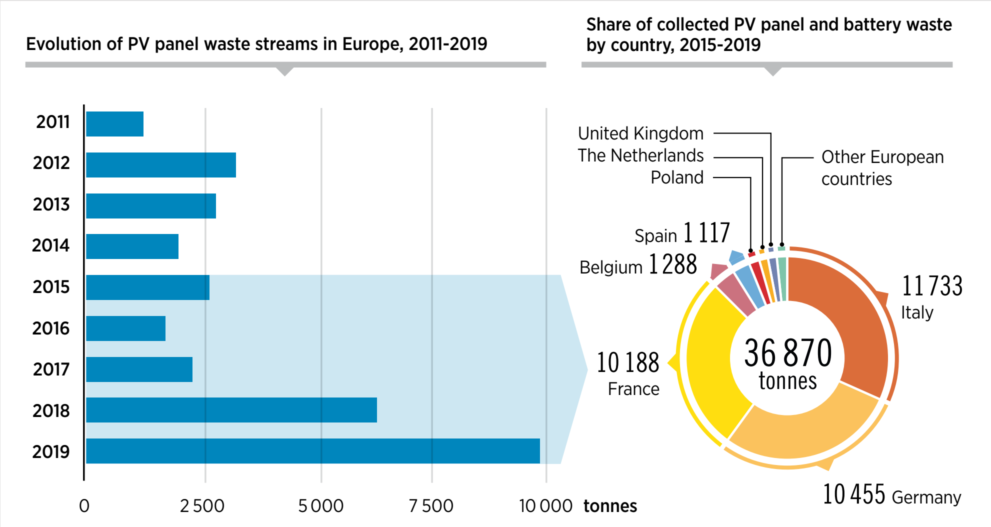
Established in 2003 and with its latest recast in 2012, the EU WEEE Directive sets ambitious rules and regulations for recycling solar PV panels. More specifically, the directive prescribes as of early 2014 minimum collection and recovery targets for electric and electronical equipment under a legislative framework for extended producer responsibility.

To date, the European Union has reached average PV recycling rates of over 70%, with an objective of achieving 85% recovery and 80% reuse and recycling. Between 2011 and 2020, almost 45 000 tonnes of waste were collected and treated by PV CYCLE, a not-for-profit-association created by the European PV industry to organise a collective take-back and recycling scheme for PV panels (Figure 4.19) (PV CYCLE, 2021).

However, some challenges remain in the end-of-life management of photovoltaics. These involve among other (1) collection (volumes need to reach certain levels to be profitable), (2) logistics (distance to recycling facilities, access to remote areas) and (3) financial costs (cost-benefit ratio of material value recovery vs. end-of-life management costs) (Deutsche Umwelthilfe, 2021; PV CYCLE, 2021; IRENA and IEA-PVPS, 2016).

End-of-life management offers significant employment opportunities, particularly in the waste industry. Currently, the European waste sector accounts for less than 1 million employees and 0.4% of the EU's employment and GDP (European Commission, 2018). Labour market growth in this sector is expected to be boosted by additional circular economy policies under the EU's Green New Deal.

FIGURE 4.19 Overview of EU PV recycling operations, by year and by country, 2019



Note: Other European countries include Austria, Bulgaria, Czechia, Denmark, Greece, Hungary, Luxembourg, Romania, Slovakia and Switzerland.

Source: PV CYCLE, 2021.

4.3.5 Support community and citizen engagement

Community energy, the "economic and operational participation and ownership by citizens or members of a defined community in a renewable energy project", can play an important role in accelerating renewables deployment while generating local socio-economic benefits and increasing public support for local energy transitions (IRENA Coalition for Action, 2018). A diverse range of community energy ownership models can already be found throughout the world, such as in Europe, North America and increasingly in developing countries such as Costa Rica, Mali and the Philippines (IRENA Coalition for Action, 2020b).

Policy makers can stimulate community energy deployment by implementing enabling frameworks that help promote market entry for community energy projects and putting financial measures in place to de-risk early-stage activities, offset capital costs and provide communities with access to affordable and low-cost financing. Further, administrative measures like one-stop shops can support communities in navigating the complex process of developing a renewable energy project as well as help with skills development and capacity building (IRENA Coalition for Action, 2020b).

Governments are adopting policies that value direct citizen participation in renewable energy projects. In countries such as Germany, Denmark and Japan, different forms of community energy have emerged that encourage citizen ownership of renewable energy projects next to accelerating local socio-economic development (IRENA Coalition for Action, 2020b). Renewable Energy Communities are now enshrined in EU law, and need to be considered by Member States in support schemes.

Community energy can play an important role in accelerating renewables deployment while generating local socio-economic benefits and increasing public support for local energy transitions.

4.4 HOLISTIC GLOBAL POLICY FRAMEWORK

Policies to advance the energy transition closely interact with one another and have implications for the energy system, economy, society and planet. An integrated policy approach would account for feedback among the policies, and across systems, to ensure a timely, just and fair energy transition trajectory.

A holistic global policy framework is, necessary to guide climate action under the 1.5°C Pathway and reinforce the energy transition at a national level. Climate policies, including fiscal policy aligned with climate objectives, represent an important component of such a framework. A diverse portfolio of measures and instruments focused on enabling and supporting the transition must be integrated into a wider and transparent policy strategy that accounts for the fact that policies introduce strong links and feedback between energy, economic and social systems.

Policies, such as carbon pricing and taxes on transport fuels, that intend to reduce consumption-related emissions could disproportionately affect low-income groups (Andersson and Atkinson, 2020). Government revenues from the implementation of climate policies can offset the regressive effects through measures such as targeted low-income household subsidies and lump sum payments. In the Canadian province of British Columbia, for instance, low-income households are provided with direct transfers to reduce the burden imposed by a carbon tax (Canada's Ecofiscal Commission, 2016; Beck *et al.*, 2015). A focused effort is needed to not just design policies with a view to scale up deployment of energy transition solutions, but also consider their feedback across the energy sector, economy and society and introduce a holistic policy basket to address concerns.

To this end, the macroeconomic analysis presented in Chapter 5 incorporates a climate policy basket that accounts for the need for an integrated approach to address equity concerns and integrates a host of measures, for instance, earmarking part of the increased government revenue to transition-related investments (discussed further in Section 5.1).

Global policy frameworks are necessary to mobilise public financing to reinforce the energy transition across all regions of the world.

Public investment will play a crucial role in the energy transition, including in the implementation of policy portfolios. Beyond direct investments in technology deployment (where private capital is hard to attract or requires de-risking), including infrastructure development (*e.g.*, networks, charging infrastructure), public investments will be crucial to implement enabling and just transition policies (*e.g.*, capacity building, social protection measures, education and retraining) as well as fossil fuels' phase-out. The American Jobs Plan aims to strengthen public investments to the tune of 1% of GDP annually over eight years focusing on key areas advancing the energy transition, including incentives for the roll-out of a national network of electric vehicles charging infrastructure and policies to promote equitable access (The White House, 2021). As discussed earlier, in Germany, a series of auctions have been conducted to seek bids from coal operators to prematurely close down power plants in exchange for awarded compensation (Appunn, 2021).

Public financing is needed to shape and guide the energy transition's trajectory, ensuring positive impacts across key socio-economic indicators. Public funding requirements for energy-transition-related policies are not always included in traditional assessments of energy transition pathways but must be accounted for and planned. While advanced economies are best positioned to mobilise public financing, global policy frameworks are necessary to mobilise such funding to reinforce the energy transition in the rest of the world. Emerging economies can benefit from international co-operation to support closure of plants, communities in transition, repurposing/rehabilitation, retraining and skilling, among other priorities. Several development finance institutions have introduced programmes to fund a just transition, such as the Energy Transition and Coal Phase-Out Programme in Asia and the Support to Energy Transition in Coal Regions in the Western Balkans, Ukraine, among other countries (Brookings, 2021).

Justice and equity are the pillars underpinning the global collaborative framework that an ambitious energy transition requires.

International climate finance has a key role to play in providing public financing necessary for a just and fair energy transition. Its function will vary from context to context – fossil-fuel-dependent communities and countries will require targeted efforts to unwind lock-ins to the fossil fuel economy and plan an alternative development trajectory based on new energy sources and economic activities (CPR, 2021). Countries where mitigation requirements consistent with climate targets go beyond their fair share of the global mitigation burden will require support to trigger the needed collaborative framework and leapfrog to climate-consistent energy systems and reap their share of the transition's benefits.

Now more than ever, public policies and investment decisions must align with the vision of a sustainable and just future. Making this happen requires a broad policy package – one that tackles energy and climate goals hand in hand with socio-economic challenges at every level. A just and fair transition leaves no one behind. Moreover, justice and equity are the pillars underpinning the global collaborative framework that an ambitious transition requires.

Ultimately, the success of the energy transition in mitigating the climate crisis will depend on the policies adopted, the speed of their implementation and the level of resources committed. In our interconnected world, international co-operation and solidarity are not only desirable, they are also vital for addressing climate change, economic inequality and social injustice. Moving forward, investment decisions should be evaluated on the extent to which they accelerate the shift towards an inclusive low-carbon economy. Anything short of that can seriously hamper progress towards a transformative decarbonisation of our societies (IRENA, 2020n).

4.5 CONCLUSION

Delivering on ambitions aligned with a 1.5°C Pathway will require a comprehensive set of policies to ensure a just, smooth and timely energy transition. As outlined in this chapter, such policies must consider deployment, integration, cross-cutting enabling conditions, structural and just transition aspects. The most appropriate mix will vary from country-to-country, and the policy needs are likely to evolve as markets mature, the share of renewables in the energy mix grows, and energy transition advances.

The policies strongly interact with one another with far-reaching implications for the energy system, society, economy and planet. As governments embark on defining and implementing the optimum policy mix to advance the energy transition, the feedbacks and interactions between policies must be closely considered. A fundamental change in the energy system will require policy-making that effectively accounts for these interactions and addresses potential misalignments and regressive outcomes that are likely to disrupt the pace of the transition.

A better understanding of the implications of energy transition ambitions and policies across society, economy and environment systems offers valuable design feedback to maximise benefits and reduce risks of disruption. The next chapter presents insights into the impact of the energy transition on key indicators such as GDP, employment and welfare, and highlights key climate policy conditions that can reduce potential regressive effects of energy transition policies.

05 SOCIO-ECONOMIC IMPACTS OF THE ENERGY TRANSITION

Energy transition involves systemic changes affecting economies and societies.

The energy transition goes well beyond the technological solutions required and involves deep structural changes that will affect economies and societies at large. An improved understanding of these effects is crucial for policy making and for ensuring that the transition is just and inclusive. To this end, IRENA's socio-economic footprint analysis (IRENA, 2016b, 2019d, 2020o) continues to capture an increasingly comprehensive picture of the transition's socio-economic impacts.

IRENA adopts a comprehensive approach that links the world's energy systems and economies within one consistent quantitative framework, analysing impacts of the energy transition on variables such as gross domestic product (GDP), employment and welfare. The results presented in this chapter demonstrate that steps towards the 1.5°C Scenario will positively affect economic activity, jobs and welfare compared to the Planned Energy Scenario (PES), so long as an appropriately holistic policy framework is in place. Box 5.1 provides an overview of the results.

Over the course of the entire transition period, the gains will vary. Over the next decade (2021-2030), overall GDP would be 2.4% higher on average on the 1.5°C Pathway compared to the PES. Economy wide, the 1.5°C Pathway yields an average of 1.4% more jobs in the first decade while jobs in the energy sector reach around 137 million by 2030, 78% of them related to the energy transition. Renewables account for 38 million. By 2050, the Energy Transition Welfare Index is 11% higher under the 1.5°C Scenario compared with the PES.

For energy and investment roadmaps to materialise, their links with society must be well understood, clear and transparent. Effective climate policy that integrates energy and investment roadmaps with wider socio-economic policies and values is important for the energy transition. This includes measures to explicitly address the regressive effects of climate change itself, as well as the effects of other policies such as carbon pricing. Together with the comprehensive policy mix discussed in Chapter 4, this more holistic climate policy framework is imperative for a 1.5°C Pathway. Only if all stakeholders – citizens, politicians, institutions – are convinced of the need to transition the energy sector, can the collaborative effort needed to address the climate challenge arise. This is all the more important since, beyond what is being modelled, countries are moving along the pathway towards 1.5°C at various speeds, and societies and economies respond in complex ways to transitions. Education, good governance and credible policy are key ingredients to an inclusive and just energy transition. When people and communities can see the benefits of the transition, political acceptance and support will be much stronger.

For IRENA's socio-economic footprint analysis, countries' existing policies are complemented with a climate policy basket to reach energy transition targets, while addressing distributional challenges with the aim to achieve just and inclusive outcomes. Government fiscal balances are the main link between policy (including climate policy) and social systems.

This chapter begins with an overview of the climate policy basket applied in IRENA's macroeconometric model and the channels through which climate policy affects economic and social systems (Section 5.1). It then discusses the impacts of the energy transition on GDP, jobs (economy wide and energy sector specific) and welfare (Section 5.2). The chapter concludes with a brief outlook on the way forward.

BOX 5.1 Socio-economic footprint of the 1.5°C Scenario, 2030 and 2050: A snapshot

The 1.5°C Scenario is estimated to deliver positive outcomes across all socio-economic indicators analysed (*i.e.*, GDP, jobs and welfare):

- **GDP:** Additional GDP growth is spurred by investment across the many dimensions of the energy transition, leading to multiple adjustments between interdependent economic sectors. Prices respond to the different cost structures of the 1.5°C Scenario and the Planned Energy Scenario (PES), respectively, and react to investment and demand; more jobs translate into higher incomes and more consumption. The 1.5°C Scenario provides an initial boost to GDP of 2.4% on average over the next decade (over the PES) that is well aligned with the needs of a post-COVID recovery. Over the entire transition period to 2050, the average improvement of GDP is estimated at 1.2% over the PES. The reduced demand for fossil fuels leads to lower revenues for mining and fuel refining industries, as well as for governments through fossil fuel rents, thus resulting in negative GDP impacts in some countries. This highlights the need for a holistic policy framework that addresses structural changes reducing fossil fuel dependency.
- **Jobs:** The global effect on jobs from the energy transition is positive. In the energy sector, jobs exceed the PES by 26 million in 2030 and are still 8 million higher in 2050 despite the decrease in fossil fuel jobs. Specifically, in the renewables sector, jobs could reach 43 million by 2050 under the 1.5°C Scenario – a 93% increase from the PES. Qualifications, skills and occupations under the more ambitious 1.5°C Scenario increasingly pertain to construction and operation and maintenance. Training for such occupations is relatively easier and offers more opportunities for fossil fuel workers. The educational requirements of the labour force evolve during the transition with a continuous increase in the share and number of workers with a primary education and a peak by 2030 of workers with a tertiary education.
- **Welfare:** The Energy Transition Welfare Index used in this report covers five dimensions (economic, social, environmental, distributional and energy access) and for the first time reports the distributional and energy access dimensions which are often overlooked in other analyses. The 1.5°C Scenario performs better than the PES along all welfare dimensions. By 2050, the 1.5°C Scenario provides a 11% improvement in the overall Energy Transition Welfare Index over the PES, with improvements of 30%, 23% and 7% in the environmental, social and energy access dimensions, respectively. On average from 2021 to 2050, the 1.5°C Scenario provides a 37% improvement in the distributional dimension over the PES.

5.1 THE CLIMATE POLICY BASKET

Climate policy plays a pivotal role in the success of energy transitions. In IRENA's macroeconometric model, a diverse portfolio of measures addresses transition and social challenges. This approach adds emphasis on how the energy transition benefits people, and on leaving no one behind. In addition to policies focused on deployment, integration and enabling factors, presented in Chapter 4, this climate policy basket includes a diverse set of fiscal policy measures, such as adequate carbon pricing applied to emissions across sectors, subsidies and public investment in infrastructure and expenditure on efforts to ensure a just transition.

This climate policy basket includes the measures necessary to move towards the 1.5°C target. Yet it leaves ample room for countries to develop their own respective policy approaches, an aspect that increases trust and acceptance by building on established local policies. The climate policy basket also manages fiscal balances in a manner that addresses the potentially regressive impact of other climate policies. Fiscal surpluses are redistributed by recycling them into the economy through lump-sum payments in a progressive way. In case of fiscal deficits beyond historical trends, the additional deficit burden is shared between citizens (additional income taxes) and government deficit spending.

Climate policy plays a pivotal role in the success of energy transitions.

In its socio-economic footprint analysis, IRENA uses a macroeconometric modelling framework that captures the effects of the different climate policies and their feedback loops. This chapter discusses the resulting structure of the cumulative global government balances for the 1.5°C Scenario, both in terms of revenues and spending, with a focus on the main elements directly affected by the transition.[1] Table 5.1 shows the revenue and spending flows included in the modeling of government fiscal balances, providing its shares in cumulative terms (2021-2050) at the global level.

Government revenue streams stand to change, through direct and induced macroeconomic effects on general taxation and declining fossil fuel export revenues, while carbon pricing will in turn provide additional resources. Revenues from public energy transition-related investment may also provide positive contributions, as does international climate finance. Carbon pricing plays a significant role, though still relatively small compared to the general revenue streams[2] (income, value added tax and social security contributions). The direct burden of carbon pricing on citizens is kept as low as possible by implementing a differentiated carbon pricing structure with lower prices for the use of fossil fuels in households and road transport (see Box 5.2). As fossil fuel use is phased out in the 1.5°C Scenario, the revenue stream for governments from fossil fuel exports (oil rent) declines, while revenues from public energy transition-related investment, such as renewable power generation, power grids and flexibility, electric vehicle (EV) charging and hydrogen infrastructure, grow. Financial flows from international climate co-operation also provide significant revenues.

Fiscal measures can address potentially regressive impacts of the energy transition.

1 The main standard fiscal balance components are indirectly affected by the transition, with the modelling framework used by IRENA also capturing these effects.

2 Note that general revenue streams are still higher than those presented, since the macroeconometric model captures only those revenue streams with macroeconomic implications.

TABLE 5.1 Elements included in the modeling for government fiscal balances, (% of global cumulative fiscal balances 2021-2050)

GOVERNMENT REVENUE	% SHARE	GOVERNMENT SPENDING	% SHARE
Regular income tax	84.6	General government spending	85.9
Value added tax		Benefit payments	
Social security contributions			
Carbon tax	7.8	Lump-sum subsidies for households	7.6
Household fuel tax	0.4	Cost of early power plant closures	0.1
Transport fuel and vehicle registration tax	3.0	Subsidies to support the transition	2.5
Oil rents	1.3	Fossil fuel subsidy payments	0.2
Additional income tax for revenue neutrality	0.2	Contribution to international co-operation	0.9
Receipts from international co-operation	1.0	Energy-related investment by government and loans	2.4
Revenues from public-energy-related investment	1.7	Additional social spending	0.4

Note: Since the model only tracks the fiscal flows that have a macroeconomic impact for the energy transition, the shares presented in the table do not reflect the shares corresponding to the full government revenues and spending. More specifically, the following fiscal flows are not fully represented: regular income tax, value added tax, social security contributions, general government spending, and benefit payments.

BOX 5.2 Carbon pricing in IRENA's modelling exercise

Carbon pricing aligned with climate goals helps level the playing field, as outlined in Chapter 4. More ambitious mitigation goals require higher carbon prices, while greater policy diversity can allow for lower prices. IRENA's modelling exercise uses carbon pricing at levels consistent with mitigation goals in combination with a diverse climate policy basket.

While carbon pricing is an important component of climate policies, its potentially negative impacts on consumers make it a complex policy tool. Social, and hence political, acceptance rests on clear and transparent communication of potential impacts, real and perceived, and on a convincing alignment with transition and social needs. Policy makers must devise ways to harmonise new fiscal instruments like a dedicated carbon tax with existing taxes on fuel use. More broadly, they also must manage and address the direct impact of such policy changes on citizens, including any regressive effects.

The policy basket for the 1.5°C Scenario, as outlined in this chapter, addresses these issues by:

- Alleviating direct impacts on citizens through lower carbon prices applied to household consumption and road transport, using already established fiscal policy instruments (fuel and registration taxes);
- Distinguishing between current operating expenses and expenditure on new equipment (*e.g.*, vehicles); and
- Earmarking revenues from carbon pricing for transition-related public investment, as well as for subsidies to support lower-income groups.

Positive government fiscal balances are re-circulated to citizens in the form of lump-sum payments to mitigate negative socio-economic impacts. Where fiscal balances are negative,[3] the burden of addressing them is distributed between an increase of fiscal deficits and higher income taxation. Finding the right level of carbon pricing is difficult. Annex 5.1 discusses the implications of carbon pricing levels set lower or above the optimum. Integrated energy-economy models can inform the balance between positive and negative impacts, but due to modelling limitations and the complexity of socio-economic systems, these estimates must be interpreted with caution and further refined through a holistic approach to policy making.

3 Always in accordance with econometrically estimated boundaries based on past data.

Government intervention is required for an inclusive transition.

Government spending plays a crucial role in the energy transition, including in addressing social challenges associated with a change from the status quo. General spending and benefits (such as for infrastructure, health, education, social security and subsidies for a wide variety of purposes) are regularly paid out by governments. The energy transition will involve additional expenditure with long-term socio-economic dividends as presented in this chapter. Several government spending streams may significantly change: fossil fuel subsidies will be reduced while transition-related subsidies and public investment will need to increase; covering the losses from stranded assets may also increase government spending; and addressing the justice and fairness requirements of the transition and existing social challenges (including distributional aspects) will require additional expenditures. Last but not least, how fiscal balances are managed may also play a significant role during the transition, with important synergies with stimulus packages to address the COVID-19 crisis. The spending needs are likely to grow the longer action towards the energy transition is delayed.

Earmarking public funds for the transition is an important part of the fiscal policy implemented in the 1.5°C Scenario. Public expenditure is used for direct public investment and loans (for infrastructure, facilities and equipment) in support of energy efficiency, end-use renewables, heat pumps and electric or fuel cell vehicles, as well as for addressing stranded assets. Different purposes require public investment to different degrees, for instance, the building sector will require greater public participation than renewable energy for power generation, while the electrification of public transport requires more than the electrification of private vehicles.

4 The G7 environment ministers have recently agreed to stop funding coal-fired power stations in developing countries by the end of 2021, signalling increasing commitment to a 1.5°C Pathway.

5 Transition-related subsidies include: energy efficiency, renewables in end-uses, green hydrogen, heat pumps, EV and EV charging infrastructure, and energy storage.

6 Such as the German Coal Phase-out Act, for example.

International co-operation is an essential piece of the global energy transition.

In the policy basket introduced in IRENA's socio-economic modelling for the 1.5°C Scenario, public expenditures are also used to address the requirements of a just and fair energy transition, covering both domestic and international needs, based on international co-operation. Countries contribute to the joint effort according to their respective capability and responsibility. The financial flows from international co-operation are earmarked for three purposes in the IRENA analysis:

- *Enabling the energy transition and addressing social challenges.* This includes addressing potential misalignments from the energy transition, such as educational and skills requirements to accommodate the transition, retraining of workers from industries that are phased-out, social policies to address economic restructuration and legacy dependencies on the fossil fuel economy.
- *Ensuring a just transition across the globe.* This includes providing support for countries with high socio-economic dependence on fossil fuel activity.
- *International fair transition elements.* Developing countries will need particular attention, based on the acknowledgement that fair emissions in many cases exceed necessary global emission reductions. Countries whose climate mitigation requirements surpass their fair share of the global mitigation burden require support to leapfrog to climate-consistent energy systems and reap their share of the transition benefits.

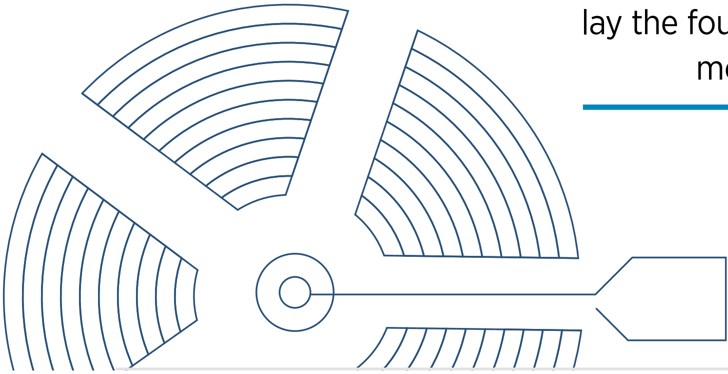
Under the energy transition scenarios, the revenue components of government fiscal balances are responding to economic developments (*e.g.*, changes in aggregated economic activity impacting taxes, shifting away from fossil fuels reducing rents). Investment in the energy transition also creates flows and feedback loops in the real economy. Additional demand leads to additional output and employment, in those sectors critical to the energy transition and along the value chain. This manifests in additional GDP and differences in employment between the PES and the 1.5°C Scenario. IRENA's socio-economic modelling captures the implications of all these factors while envisioning an international collaborative framework to address climate change.

5.2 SOCIO-ECONOMIC FOOTPRINT RESULTS

Renewable energy and energy efficiency represent key technological avenues of the energy transition with significant interactions and feedbacks with wider economic, social and planetary systems. Underpinned by a comprehensive policy framework (as elaborated in Chapter 4), the energy transition can lay the foundations for building more resilient societies.

IRENA's cost-benefit analysis shows that when the reduced externalities from lower air pollution and avoided climate change are combined, the overall benefit of the energy transition is valued at between USD 2 and USD 5.5 saved for every additional USD 1 spent (see Box 5.3). The sub-sections that follow consider the socio-economic footprint of the energy transition analysed in terms of GDP, employment and welfare.

The energy transition can lay the foundations for building more resilient societies.



BOX 5.3 Transition cost-benefit analyses

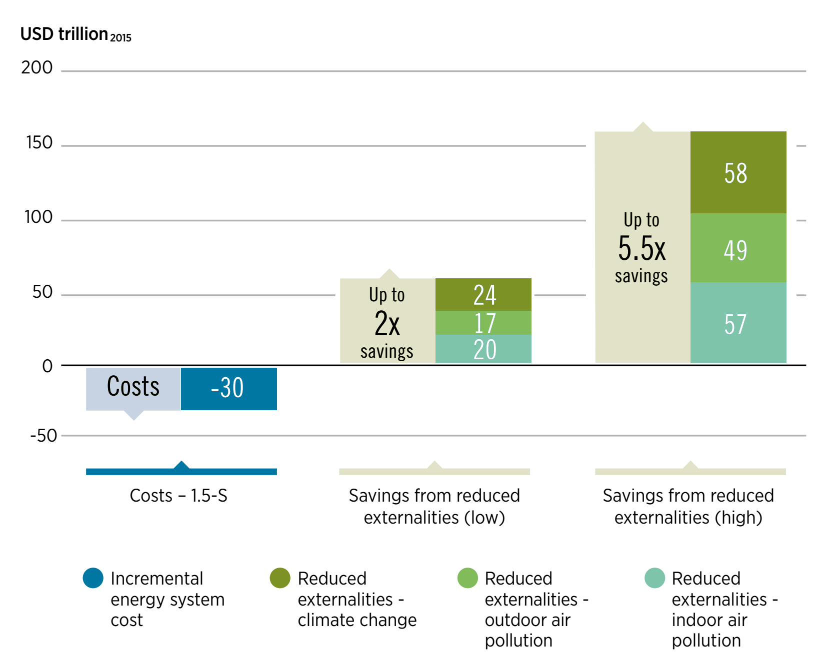
A broad view of the balance between the costs and benefits of the energy transition can be obtained by using estimates of externalities related to pollution and climate change and comparing them with transition costs, including investments, operation and maintenance expenditures and subsidies.

The overall balance of the energy transition is positive, with benefits greatly exceeding costs. IRENA estimates that in the 1.5°C Scenario every USD 1 spent on the energy transition would yield benefits from reduced externalities valued at between USD 2 and USD 5.5. It should be noted that exogenous estimates of externality costs have a significant uncertainty, as reflected in the range of benefits expected from the transition (Figure 5.1). In cumulative terms, the 1.5°C Scenario would have an additional energy-system cost (net effect of increased investment and reduced operation and maintenance costs) of USD 30 trillion over the period to 2050 but would result in a payback through reduced externalities from human health and the environment of between USD 61 trillion and USD 164 trillion.

The savings from reduced externalities fall into three broad categories: outdoor air pollution, indoor air pollution and climate change. Two externalities are included in this cost-benefit analysis:

- Air pollution externalities are the largest component, making up roughly two-thirds of the total. (Indoor pollution largely results from using traditional biomass.) The reduced externalities from lower levels of air pollution alone range from USD 37 trillion to USD 106 trillion over the period. These savings are at minimum slightly above the additional cost required for the 1.5°C Scenario, but are potentially as high as three times that amount.
- The other significant source of reduced externalities is related to climate change. These externalities are quantified using the social cost of carbon approach (Intergovernmental Panel on Climate Change estimates) to put a value on each tonne of CO_2 that is avoided through the measures outlined in the 1.5°C Scenario. The reduced externalities from avoided climate change impacts account for savings ranging from USD 24 trillion to USD 58 trillion over the period.

FIGURE 5.1 Cumulative difference between costs and savings of 1.5°C Scenario compared to the PES, 2021-2050



Based on IRENA's analysis.

In the 1.5°C Scenario, every USD 1 spent on the energy transition would yield benefits from reduced externalities valued at between USD 2 and USD 5.5.

5.2.1 Economic growth as measured by gross domestic product

Under the PES, real GDP (following a short period of recovery from the impacts of COVID-19 in 2020) is expected to rise at a compound annual growth rate (CAGR)[7] of 2.9% between 2021 and 2050. While this may be interpreted as moderate growth, it should be noted that it implies significant stress on the planet's resources and ecosystems. In fact, in the PES the energy and carbon intensity of the economy is reduced substantially compared to today, but not enough to address climate change. Table 5.2 summarises key trends under the PES over the next three decades. Global population is assumed to grow at a CAGR of 0.8% in the first decade and 0.3% in the second decade. Global labour force development reflects past and future population growth and a projection of participation rates.

TABLE 5.2 Key economic and demographic trends of the PES (compound annual growth rates)

VARIABLE	2021-2030	2030-2040	2040-2050
Real GDP	2.7%	2.9%	2.5%
Labour force	0.6%	0.4%	0.2%
Total population	0.8%	0.4%	0.3%

Source: The projections are constructed using a comprehensive set of international data sources. The main source for population data is the United Nations (World Population Prospects) and for GDP forecasts it is the World Bank's World Economic Outlook. These are supplemented with data from the International Labour Organization, Organisation for Economic Co-operation and Development (STAN), World Bank and Asian Development Bank databases and the European Commission (AMECO, Eurostat, EC Annual Ageing Report, EU Reference Scenario reports).

7 The CAGR is a measure of growth over a given period – in this instance 2021-2050. It can be thought of as the constant annual growth rate needed to move from an initial to a final value over a specified period.

1.5°C Scenario sees a boost in global GDP.

The energy roadmap presented in this report includes the policies outlined in Chapter 4 and leads to investments in the energy transition substitute by: as documented in Chapter 3. All these are used as inputs to the macro-econometric model. Changes in prices (of energy and general goods and services) and global and regional trade impacts are evaluated in a macro-econometric model that tracks economy-wide feedback loops and dynamics with high sectoral and geographical granularity.

Under the 1.5°C Scenario, global impacts[8] on aggregated economic activity are positive. Compared with the PES, from 2021 to 2030, the level of GDP is on average 2.4% higher in the 1.5°C Scenario. Figure 5.2 offers a detailed view of the various drivers[9] that cause the difference between the two scenarios. Investment in the energy transition is the largest driver of the positive GDP effect over time.

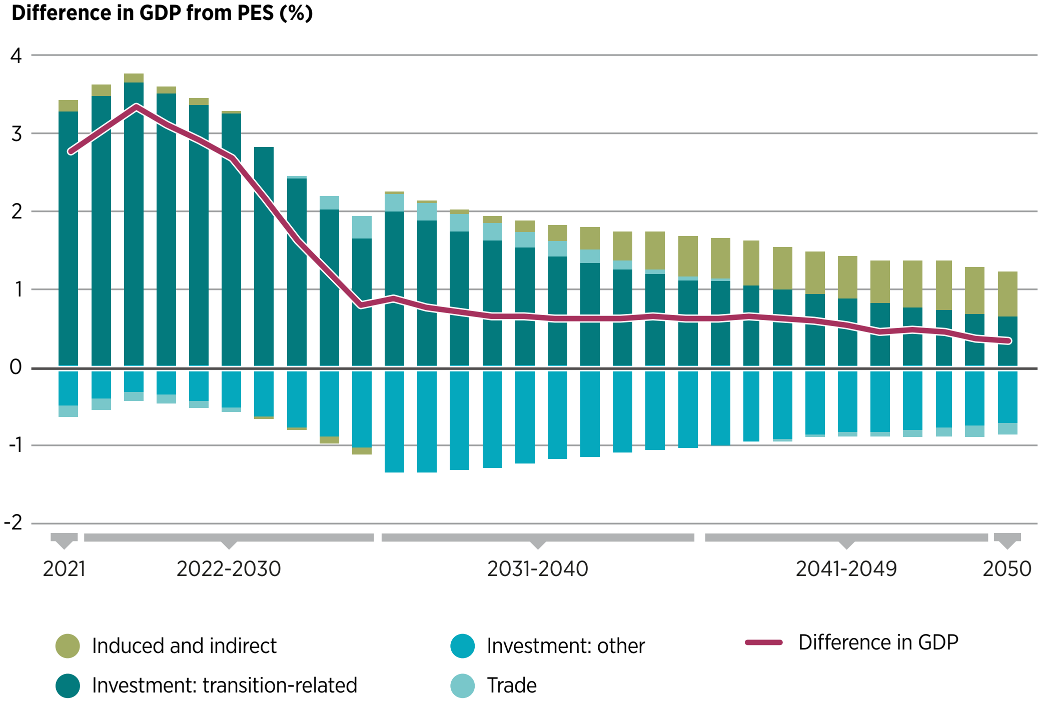
With a growing consensus on the need for a green recovery from the COVID-19 crisis, much-needed investments to boost economies must be in sync with a 1.5°C Pathway. IRENA's 1.5°C Scenario reflects this by putting a large share of the necessary investment in the first decade of the period considered. IRENA's modelling approach allows trends in GDP and other economic or welfare indicators to be traced over time, and is thus capable of showing how front-loaded investments in the first decade can yield the desired post-COVID stimulus effects and how these economic impacts evolve over the long term.

Given front-loaded investment in a 1.5°C Scenario, the difference to the PES scenario with its delayed plans of action is the largest at the beginning, reaching over 3% (see Figure 5.2). Infrastructure investment in the energy transition will boost domestic economies directly and along the respective value chains. The overall economy picks up this positive impulse and spill-over effects (*i.e.*, indirect effects along the value chain) and induced effects contribute positively.

8 Country and regional results may differ significantly from global aggregates, with some countries/regions showing still more positive impacts of the energy transition on economic activity and vice versa.

9 IRENA's analysis uses a more nuanced description of drivers and their effects, but here drivers have been grouped for clarity.

FIGURE 5.2 **GDP difference between the 1.5°C Scenario and PES, with GDP drivers**



Note: **Transition-related investment** includes the effects of changes in investments on transition-related categories such as renewables for power generation and end uses, energy efficiency, power grids and flexibility, electrification and hydrogen and electric vehicle infrastructure. Government transition-related spending is also included here. **Other investment** includes fossil fuel supply, crowding out and any endogenous responses in investment (for example, to changes in prices of production). **Trade** includes net trade in fuels and any endogenous responses to other trade (for instance, as a response to price and wage changes). **Induced and indirect** effects include the effects of changes in taxes (income, value added tax) such as those due to oil rent losses, revenue recycling through lump-sum payments, aggregate prices and other changes in consumer expenditure (including reallocations and indirect effects).

Investment impacts on GDP

The investment driver, which includes both transition-related and "other" investments, has an overall positive effect on GDP during most of the transition, particularly during the ongoing decade.

Transition-related investment covers any investment in renewable energy in the power sector and in the end-use sectors, as well as investment in energy efficiency, in the grid and EV infrastructure, energy flexibility and energy system integration (including hydrogen). This investment leads to additional demand across economic sectors, such as the manufacturing of equipment, construction and service sectors such as retail, business services or IT. The overall effect is positive and represents the largest contribution to GDP. It should be noted that government spending to support the energy transition significantly contributes to these improvements as it focuses on transition-related needs, facilitates investments by the private sector and allocates expenditure to support a just and fair transition. Governments' involvement in the transition is underpinned by international co-operation to ensure that the burdens and benefits of the transition can be more equitably shared.

Other investment includes that in fossil fuel supply, crowding out and any endogenous responses (*e.g.*, to changes in prices of output). The shift away from a fossil-fuel-based energy system in the 1.5°C Scenario implies a sharp reduction of investment in fossil fuel supply compared with the PES. The additional energy sector investment needs of the energy transition (USD [2019] 33 trillion more in 1.5°C Scenario than in the PES in cumulative terms) will partially crowd out[10] investment from other economic sectors that would have taken place under the PES, thereby contributing to the negative impact on GDP.

Induced and indirect impacts on GDP

The overall impact of induced and indirect effects on GDP is positive. This impact includes: (1) the positive contribution of increased consumer expenditure due to changes in general taxation (*e.g.*, income and VAT), revenue recycling though lump-sum payments, reallocations and other indirect effects; and (2) the negative impact of aggregate price effects and loss in government oil rents.

Revenue recycling through lump-sum payments (besides addressing the regressive impacts of climate change and other transition policies) provides stimulus for consumption in the lower segment of the income distribution. Also, increased government revenues from higher GDP allows for reduced general taxation, thereby further inducing private consumption.

The resulting overall price levels put downward pressure on GDP throughout the period, especially in this decade. Carbon prices, technology costs, fossil fuel subsidies, wage responses (affecting labour costs) and the domestic response to changes in prices all play a role.

Losses from oil rents also have a negative impact as they may need to be compensated by governments to maintain budgets and governmental services. At the global level, the negative impact is relatively small but significant,[11] and higher between 2030 and 2050. The loss of value in the oil and gas sector is attributable to both lower global oil prices in the 1.5°C Scenario and lower extraction volumes.

10 Crowding out investment at the level of industries and governments reflects that investment in the energy transition is not fully additional. Some portion replaces investment that would have otherwise taken place under the PES scenario.

11 For countries with high dependence on fossil fuels the negative impact of lost oil rents is much higher, with a stronger influence on GDP.

Trade impacts on GDP

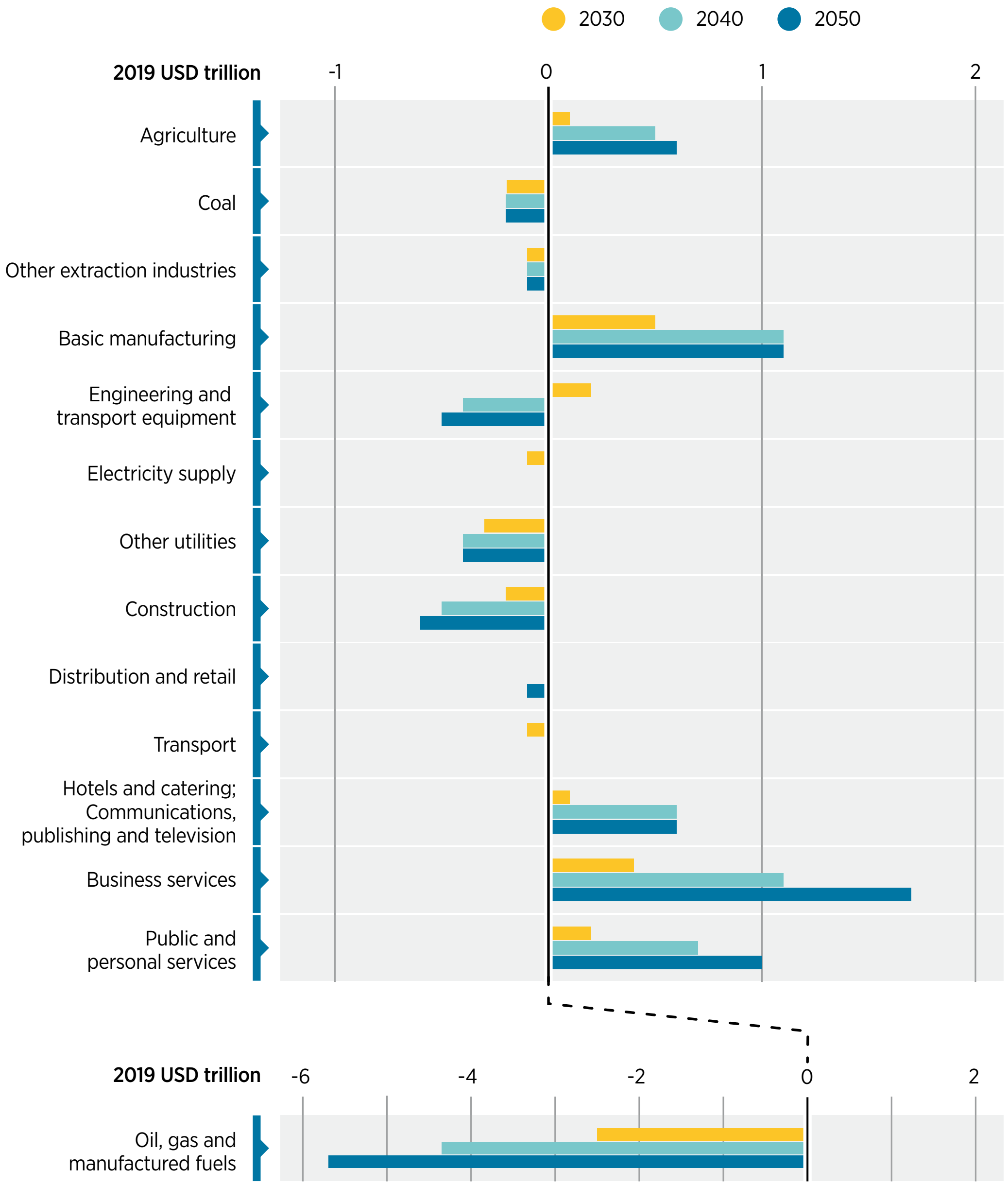
Trade effects encompass changes in net trade in fuels and any endogenous responses to other trade (for instance, as a response to price and wage changes). At the global level such effects are relatively small, since their aggregate represents the balance between some countries/regions having positive effects and others negative effects. At the country or regional level, however, trade effects may have a significant impact.

Net fuel trade globally has a positive effect for much of the forecast period before nearing a zero balance by 2050. Consumption of manufactured fuels is much lower in the 1.5°C Scenario than in the PES throughout. Some countries lose revenues from fuel exports throughout the period to 2050, while others experience a strong reduction in fossil fuel imports, with its associated positive effect on GDP. By 2050, the net trade balance in fuels becomes a negligible proportion of the positive GDP impact. The impact of the 1.5°C Scenario on different countries' prices introduces changes both in the relative competitiveness and import/export dynamics of non-energy products, which alters the non-fuel trade balance. Net changes in other trade are negative at the global level throughout the considered time frame.

Changes in economic structure

Figure 5.3 shows the difference in output between the 1.5°C Scenario and PES for different economic sectors, and thus gives an indication of how the overall **economic structure** is affected by the energy transition. Most impacts are amplified over time, independent of the direction (*i.e.*, as negative effects become more negative and positive effects become more positive). The *oil and gas and manufactured fuels sector* experiences the most negative impacts, with a difference in output between the 1.5°C Scenario and PES that reaches USD (2019) -5.7 trillion by 2050. Manufacturing sectors gain over time, mainly providing the equipment and technologies for the energy transition. Between 2030 and 2050 the difference in output between the 1.5°C Scenario and PES is about USD (2019) 1.1 trillion per year. The agriculture sector (including forestry) benefits from the higher demand for biomass and biofuel inputs under the 1.5°C Scenario, reaching a difference in annual output between the 1.5°C Scenario and PES of USD (2019) 0.6 trillion by 2050. The largest benefits accrue in the three aggregated categories of *services*, where the total difference in output between the two scenarios is USD (2019) 3.3 trillion by 2050. Compared to PES, the 1.5°C Scenario features more demand for consulting, planning, financial, legal and administrative services, while higher consumption pathways lead to additional demand for leisure activities and respective services.

FIGURE 5.3 Differences in economic output between 1.5°C Scenario and PES, by sector



Based on IRENA's analysis.

Impact of climate change on GDP

The GDP results presented above do not include the effects of climate change for either the PES or the 1.5°C Scenario. However, climate change is already affecting economic activity, and will continue to do so to varying degrees depending on the region and emission pathway.

IRENA started exploring the implications of climate damages on overall economic activity in the Global Energy Transformation report (IRENA, 2019d), using a recently updated[12] methodology[13] that includes additional data on the impact of temperature changes on economic growth rates. The resulting estimate can still be considered conservative, since some climate change effects are not yet prominent or measurable, such as the intensification of extreme weather events (*i.e.*, wildfires, flooding and tropical storms), sea level rise, the crossing of climate tipping points, and resulting trade disruptions, and the potential knock-on effects of complex political and social processes hastened by the stresses of climate change (*e.g.*, mass migration; IRENA, 2019d).

Climate change damages aggregate economic activity in both the 1.5°C Scenario and PES, but to a differing degree according to cumulative CO_2 emissions during this century. Figure 5.4 outlines effects on GDP in both scenarios,[14] compared with GDP results (presented above) under the assumption of no climate damage effects. While both scenarios entail negative impacts, the significantly lower cumulative emissions of the 1.5°C Scenario compared to the PES scenario imply less climate-related damages, supporting the benefits of transitioning swiftly to a clean energy future. In 2050, the difference in GDP between the two scenarios rises to 3.9% as compared with 0.3% when climate damages are not factored in (Figure 5.4).

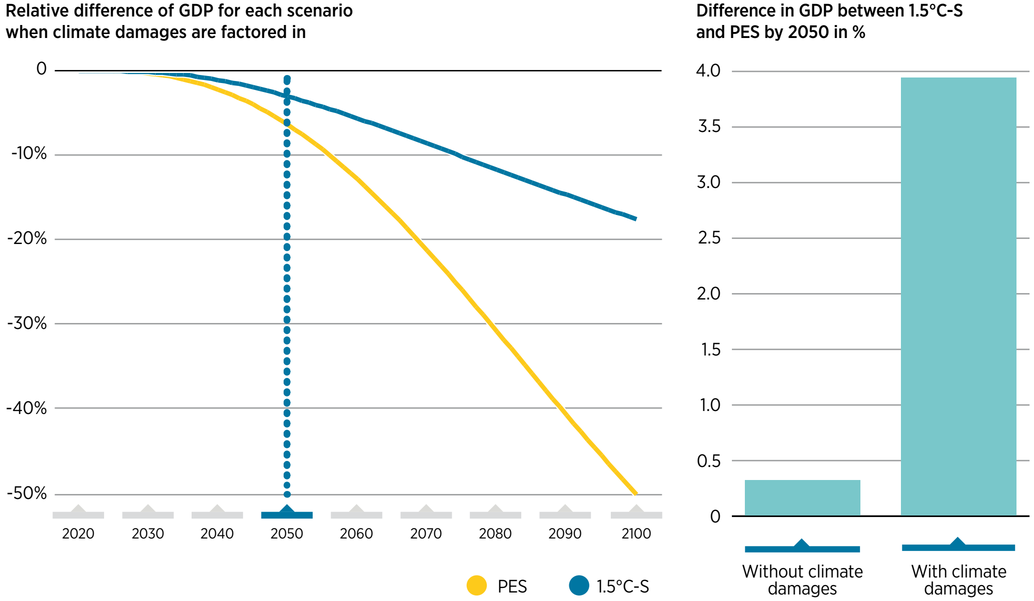
The results presented in this sub-section show how, globally, GDP responds positively to the energy transition, with better performance in the 1.5°C Scenario than in the PES. Moreover, GDP improvements are particularly high during the on-going decade as the global economy looks to recover from the COVID-19 crisis. The positive impacts on GDP of the 1.5°C Pathway are further amplified when climate damages are factored in due to lower cumulative emissions.

12 Based on work informed by an extended dataset at a sub-national level involving over 11 000 districts (Burke and Tanutama, 2019).

13 The methodology is based on a statistical analysis to derive a non-linear damage function that maps temperature changes to economic losses, as a function of the temperature level, providing geographical details of climate damages (Burke, Davis and Diffenbaugh, 2018; Burke, Hsiang and Miguel, 2015).

14 Climate damages unfold across different time scales. Some take decades to be felt but are already in the pipeline once greenhouse gas emissions have been released to the atmosphere. This report focuses on the transition period up to 2050, when the 1.5°C Scenario reaches net zero and hence has completed its cumulative emissions. However, some of the climate damages associated to these cumulative emissions will unfold during the 2050-2100 period. The goals for global warming (like the 1.5°C Scenario) make reference to the increase in global temperature by the end of the century.

FIGURE 5.4 Effects of climate damages on global GDP under the 1.5°C Scenario and PES, for each scenario (left) and for the difference between both scenarios (right)



Based on IRENA's analysis

1.5°C Scenario implies lower impact of climate damages on GDP.

The energy transition has net positive effects on job creation.

5.2.2 Jobs in the energy transition

The employment dimension of the energy transition is particularly relevant as governments look to increase economy-wide job creation and manage misalignments in labour markets across sectors in transition. The analysis finds that the energy transition has net positive effects on job creation. The investment stimulus associated with the 1.5°C Scenario helps generate an economy-wide gain of jobs compared to the PES. The additional jobs peak around 2030 at 51 million, and by 2050 still run to 20 million. In the energy sector itself, the 1.5°C Scenario sees the number of jobs peaking by 2030 at 137 million jobs, or 26 million more than the PES. By 2050, the sector supports 122 million jobs under the 1.5°C Scenario, still surpassing the PES by 8 million jobs. The 43 million jobs in renewable energy by 2050 under the 1.5°C Scenario will be almost double the number in the PES.

This section first presents impacts on economy-wide jobs, followed by those in the energy sector as a whole and finally those most directly affected by the energy transition. The analysis provides insights on the evolution of conventional and energy-transition-related jobs as well as on the structure of renewable energy employment, its distribution across the value chain and the skills or occupational requirements needed to support this shift in the labour market.

The impacts of the energy transition on economy-wide jobs

Additional economic activity leads to more jobs under the 1.5°C Scenario compared to the PES. Figure 5.5 presents the evolution of the difference in economy-wide employment between the scenarios over time, as well as its drivers. Jobs are not linearly related to increases in output, but are influenced by increases in productivity, regional shifts in manufacturing and services, and wage trends. Moreover, the labour market does not respond instantaneously to stimulus in economic activity but progresses with sluggish responses, while increases in aggregate economic activity do not all translate into additional jobs, since part of it is captured by increased wages. Employment benefits peak before 2030, with a difference of 1.44% (51.3 million jobs) over the PES. As the transition progresses beyond 2030, these differences in employment over the PES gradually reduce until they reach 0.55% (20.2 million jobs) by 2050 (Table 5.3).

TABLE 5.3 Improvement in jobs in the 1.5°C Scenario over the PES, both in relative and absolute terms, global results

IMPROVEMENT IN THE 1.5°C SCENARIO OVER PES		2021	2027	2030	2040	2050
Relative	%	0.80	1.44	1.09	0.73	0.55
Absolute	million jobs	28.3	51.3	39.3	27.0	20.2

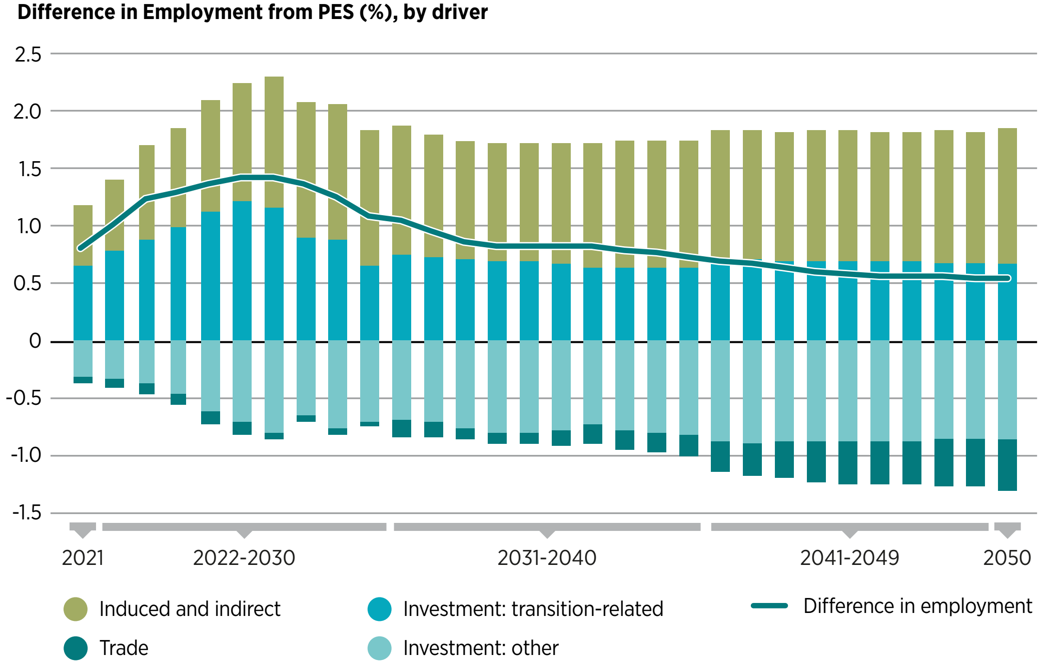
Based on IRENA's analysis.

Investment effects on economy-wide jobs. Throughout the transition period, overall employment is 0.9% higher on average in the 1.5°C Scenario than in the PES. One of the main positive impacts on employment comes from investment in the energy transition ("investment: transition related" in Figure 5.5), including grid enhancement, efficiency and, of course, renewable energy. Investment shifting from fossil fuels (extraction and power generation) and other sectors towards the energy transition ("investment: other" in Figure 5.5) leads to less labour demand in fossil fuel activities and in non-energy sectors and along their value chains. Overall, the net impact of investment on employment is positive during the first decade and becomes negative thereafter. This is a consequence of reduced investment in sectors with greater employment intensity.

Trade effects on economy-wide jobs. Trade effects on employment are negative during the entire transition, being relatively small during the first two decades but increasing thereafter. This is mainly driven by the change in trade in fossil fuels, but non-energy trade also contributes to this negative result.

Induced and indirect effects on economy-wide jobs. Induced and indirect effects have a positive impact on employment throughout the transition. Wage effects, consumer expenditure and dynamic labour market responses all contribute to this positive impact on economy-wide employment, which ultimately is the principal driver that tilts the balance towards positive employment impacts throughout the transition.

FIGURE 5.5 Employment difference between the 1.5°C Scenario and PES, by driver



Note: **Transition-related investment** includes the effects of changes in investments on transition-related categories such as renewables for power generation and end uses, energy efficiency, power grids and flexibility, electrification and hydrogen and electric vehicle infrastructure. Government transition-related spending is also included here. **Other investment** includes fossil fuel supply, crowding out and any endogenous responses in investment (for example, to changes in prices of production). **Trade** includes net trade in fuels and any endogenous responses to other trade (for instance, as a response to price and wage changes). **Induced and indirect** effects include the effects of changes in taxes (income, value added tax) such as those due to oil rent losses, revenue recirculation through lump-sum payments, aggregate prices and other changes in consumer expenditure (including reallocations and indirect effects).

At the sectoral level, the notable shift away from mining and manufactured fuels towards services, manufacturing and agriculture is shown in Figure 5.6, which presents the difference in jobs between the 1.5°C Scenario and PES across different economic sectors for 2030, 2040 and 2050. Manufacturing sees a boost in jobs required to deploy the infrastructure and equipment for the transition. The differential is more than 13 million jobs by 2030, and by 2050 still runs to more than 9 million jobs. The agriculture sector (the classification includes forestry) fares well especially during the first decades of the transition (when more than 11 million jobs are created by 2030 than under the PES), benefitting in particular from the provision of biomass feedstock. Services are needed at each stage of renewable energy deployment, grid stabilisation or increase in energy efficiency. Planning projects, licensing and carrying out audits, issuing permits, supporting financing, conducting operation and maintenance (O&M) and decommissioning are examples of these activities. Overall business services provide above 8 million jobs more than under the PES by 2050. The enhanced aggregated economic activity also contributes to the increase in service jobs, with public and personal services providing about 14 million jobs more than under the PES by 2050.

FIGURE 5.6 Employment difference by sector between the baseline and 1.5°C Scenario, thousand jobs

Based on IRENA's analysis.

The energy transition offers significant employment opportunities. Leveraging existing skills and qualifications helps to reap these benefits, and the scope for action is wide. The energy transition requires equipment, materials and services across all economic sectors, in particular when including the value chain in the analysis – *i.e.*, those materials and activities required to produce wind turbines, photovoltaic (PV) modules, insulation or DC cables needed for the transition. The distribution of the potential positive effects differs between countries and regions depending on their economic structure. Each must identify areas with the greatest potential for local value creation, and carefully plan alignment with the energy transition requirements. Planning of a wind farm, for instance, involves legal, energy regulation, real estate and taxation experts, financial analysts, logistics experts, environmental experts, health and safety experts, geotechnical experts and engineers (IRENA, 2017f). The transport equipment sector benefits from the need for cranes, buses to bring workers or trucks to bring materials. Economy-wide jobs also include those in sectors not related to the energy transition value chain, but where additional economic activity from higher incomes triggers higher consumption.

However, if the success of the energy transition rides solely on the diverging capabilities of individual countries across the world, unequal outcomes will likely follow. For more equitable results, transition strategies could aim to support the evolution of countries' economic structures aided by international co-operation within a global collaborative framework.

Jobs in the energy sector

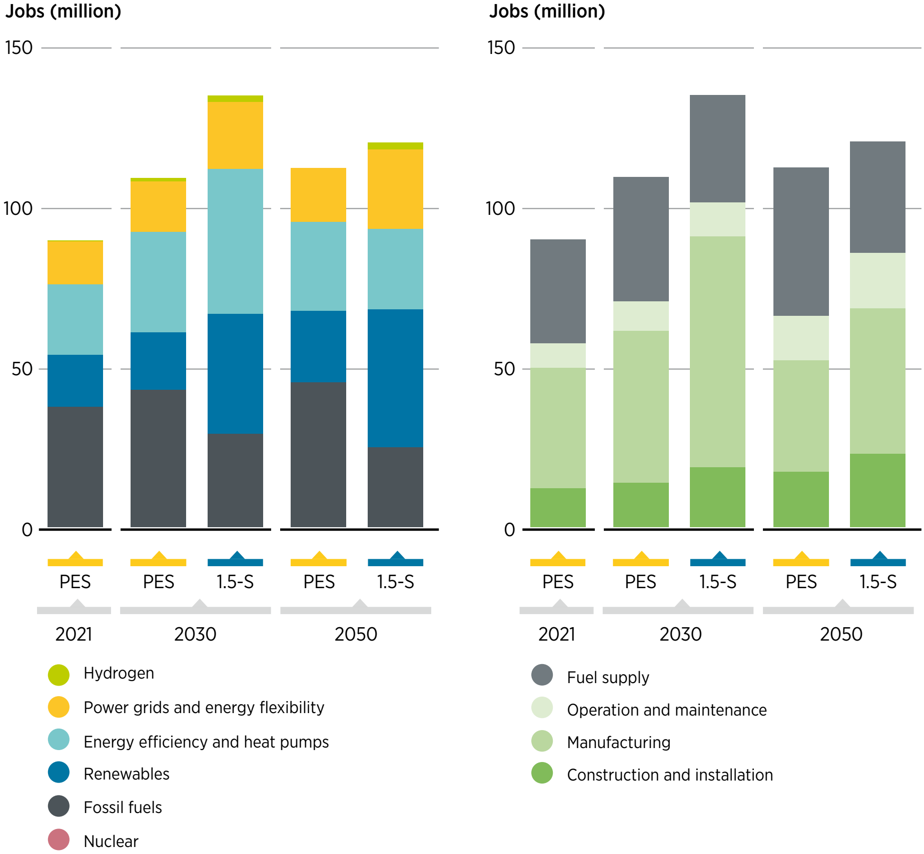
The energy sector presently contributes just above 7% of global output and accounts for about 1% of all jobs. This includes, among others, all people working in coal mining, oil and gas extraction, processing of fossil fuels as well as electricity generation, be it fossil or renewable, and O&M of electricity grids. This sub-section first discusses jobs in the energy sector as a whole and then takes a detailed look at the picture in the renewable energy sector.

Jobs in the overall energy sector

Fundamentally, the impact of the energy transition on energy employment is positive under both scenarios, but more so in the period to 2030 than in the later decades, reflecting the front-loading of investment and changes in labour intensity. Figure 5.7 gives an overview of employment in the energy sector under the two scenarios, the PES and 1.5°C Scenario, in absolute values over time. By 2030 the energy sector would have 137 million jobs under the 1.5°C Scenario, as compared with 111 million under the PES. By 2050 this difference shrinks from 26 million to 8 million. In both cases, the loss of fossil fuel jobs is lower than the increase in transition-related jobs.

Of the 137 million energy sector jobs in the 1.5°C Scenario by 2030, 107 million jobs (about 78%) are transition related. Energy efficiency is an important pillar of employment, particularly in the first decade, reaching above 45 million jobs by 2030. Renewables contribute about 39 million jobs. As the transition progresses beyond 2030, the further decrease of fossil fuel jobs in the 1.5°C Scenario is more than compensated by gains in renewables, power grids and flexibility, and hydrogen jobs.

FIGURE 5.7 Energy sector jobs by technology (left) and segment of value chain (right) under the PES and 1.5°C Scenario (million), global results



Note: 2021 estimates are obtained through a calibrated macroeconometric model based on investments associated with the PES. It should be noted that the jobs reported here for the energy sector go beyond the traditional categories (fossil fuels, electricity generation, bioenergy and nuclear) to include energy efficiency, energy flexibility, power grids, the hydrogen value chain and heat pumps.

Based on IRENA's analysis.

It should be noted that following a 2030 peak, a subsequent reduction in energy efficiency jobs brings the total number of energy sector jobs in the 1.5°C Scenario to 122 million by 2050. The 2030 peak has two main reasons: first, given the urgency to get on a more sustainable pathway, the 1.5°C Scenario begins with high investment in the first decade; second, as costs come down and technologies mature, the labour intensity decreases (*i.e.*, labour input requirements per unit of investment go down).[15] Qualifications, skills and occupations under the ambitious 1.5°C Scenario are increasingly concentrated in manufacturing, followed by fuel supply (Figure 5.7).

15 The expected improvements in labour productivity differ from technology to technology, depending on both the current degree of maturity and potential for benefiting from economies of scale.

The employment implications of the energy transition reach beyond its direct effects on the energy sector (presented in Figure 5.7). For instance, the road transport sector will also experience a shift from internal combustion engine vehicles to electric vehicles with important labour implications (Box 5.4).

BOX 5.4 The energy transition's implications for jobs in road transport

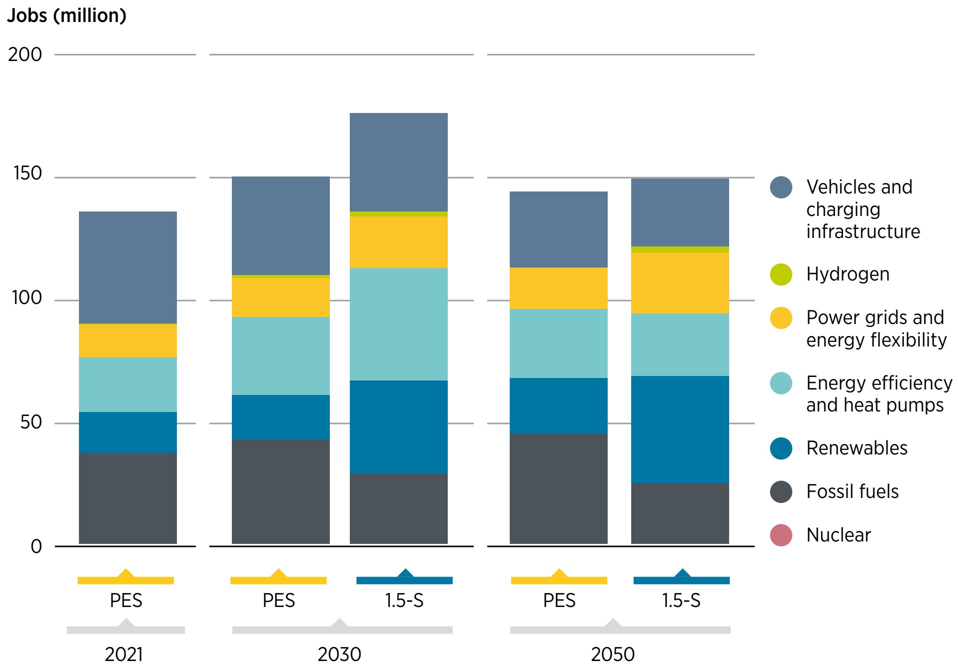
The energy transition has impacts on employment far beyond the energy sector (as presented in Figure 5.7). A case in point is road transport vehicles and the associated infrastructure. The energy transition involves a shift from internal combustion engine vehicles to electric vehicles (EVs) and fuel cell vehicles. This has deep implications for employment along all segments of the value chains producing and maintaining related equipment, given that mechanical components will be substituted by electrical ones and that the new vehicles have fewer parts. Labour intensity may be significantly lower, and there will be changes in needed skills and qualifications.

But this shift also has implications for infrastructure jobs, given the need to deploy, operate and maintain an extensive EV-charging infrastructure. The learning rates of the new vehicle technologies, the evolution of labour intensity and the room for behavioural change affecting the number of vehicles on the roads will all influence the labour market structure associated with this transition.

Figure 5.8 presents the evolution of overall energy sector jobs including vehicles and vehicle infrastructure requirements, complementing the values in Figure 5.7. By adding overall jobs across vehicle types (internal combustion engine, electric and fuel cell vehicles) and the jobs linked to EV-charging infrastructure, the total number of energy sector jobs increases from 137 to 177 million by 2030, an increase of 29%. From 2030 to 2050 the number of jobs in vehicles decreases due to the shift from internal combustion to electric vehicles and improvements in labour productivity.

The employment implications of the energy transition reach beyond its direct effects on the energy sector.

FIGURE 5.8 **Evolution of energy sector jobs by technology under the PES and 1.5°C Scenario, including vehicles and associated recharging infrastructure**



Based on IRENA's analysis.

Hydrogen jobs presented in Figure 5.7 include both electrolysers and hydrogen infrastructure. In the 1.5°C Scenario they remain stable at around 2 million jobs from 2030 to 2050, while in the PES they decline because of decreasing investment after 2030. In relative terms they represent a small share of all energy jobs, but the introduction of hydrogen in the energy system can have ripple effects throughout supply chains (see Box 5.5).

BOX 5.5 The hydrogen supply chain

By 2050, as pointed out in chapter 2, 30% of electricity use will be dedicated to produce green hydrogen and its derivatives such as e-ammonia, e-methanol and synthetic kerosene, and almost 5 000 gigawatts of hydrogen electrolyser capacity will be needed, up from just 0.3 gigawatts today. Such upscaling of the green hydrogen sector will lead to new supply chains, as seen before with other renewable energy technologies. For example, pipelines will need to connect hydrogen production points with the steel and chemical industry. Repurposing thousands of kilometres of fossil gas pipelines or building new hydrogen-ready ones will need trained piping system professionals. Hydrogen-related jobs linked to electrolysers and hydrogen infrastructure are included in Figure 5.7.

The employment impacts of the introduction of hydrogen as an important vector in the energy system has ripple effects in the supply chains of different economic sectors. The shipping industry will need professionals to repurpose ships able to consume ammonia and to build ships to transport liquid hydrogen (like the recently launched "Suiso Frontier") or e-fuels worldwide (IRENA, 2021i). The air transport industry and its supply chains will also be affected as engines are required to work with increasing shares of hydrogen. Expected actions include introducing fuel-cell-based airplanes, producing synthetic hydrogen-derived airplane fuels and managing hydrogen-derived fuels in airports. Fuel cell vehicles and their supply chains will also provide new job opportunities, in the manufacturing of equipment and its maintenance, as well as in the supporting infrastructure. Hence, the total number of jobs linked to the introduction of hydrogen in the energy system goes beyond those displayed in Figure 5.7.

Jobs in renewables

Looking specifically at the renewable energy segment of the energy sector, we find that the energy transition leads to significant jobs growth by 2030 and 2050, with the 1.5°C Pathway having a significant advantage over the PES.

In the PES renewable energy jobs increase slightly (9%) from 2021 values to reach 18 million jobs by 2030. After 2030, under the PES the deployment of renewables intensifies with a delayed response to the climate change challenge, resulting in 23 million jobs by 2050. By contrast, the 1.5°C Scenario leads to a much bigger gain, with jobs in renewables reaching 38 million by 2030 (a 130% increase from 2021 values). Thereafter, a reduced rate of deployment and increasing labour productivity attenuate the growth of renewable energy jobs, which by 2050 reach 43 million (a 15% increase from 2030 values). Comparing the two pathways, there are about 20 million additional jobs in renewables under the 1.5°C Scenario by 2050 (see Table 5.4).

TABLE 5.4 Overall renewable energy jobs in the 1.5°C Scenario and differences with the PES, global results

			2021	2030	2050
Renewable energy	Absolute	million jobs	16.5	37.8	43.3
	Difference with the PES	million jobs	-	19.8	20.8
		relative	-	110%	92.6%

Note: IRENA has been monitoring renewable energy jobs annually since 2011, which are used to calibrate the macroeconometric model to the 2019 monitored jobs. Once calibrated, the model allows data gaps to be filled for places and technologies where no employment data are available, providing a full picture of renewable energy employment in the calibration year (2019). The calibrated model is used to provide a full picture of renewable energy jobs for the different scenarios over time. The job numbers for 2021 are those forecasted under the PES.

For a deeper understanding of the job opportunities under both scenarios, detailed results for renewable energy jobs by technology are shown in Figure 5.9.

Of the 20 million solar jobs shown in the figure for the 1.5°C Scenario by 2050, 77% are PV, 15% solar water heaters (SWHs)[16] and 8% concentrating solar power. Solar PV is the single-largest source of jobs in renewables in both scenarios, but reaching a more significant number in the 1.5°C Scenario than under the PES. First, large investment sums go towards solar PV in that scenario, and second, it has a relatively high labour intensity. Labour intensity varies depending on the region where capacity is installed and the scale of the installation. Large-scale installations require less labour per megawatt than off-grid, rooftop or any other small-scale installation.

Bioenergy comprising all forms of biomass is the second-largest contributor given its high labour intensity for biofuels supply. It does not differ largely over time in the 1.5°C Scenario, due to the sustainability boundary for biomass use. By 2050 bioenergy employs 6 million people in the PES and 14 million people in the 1.5°C Scenario.

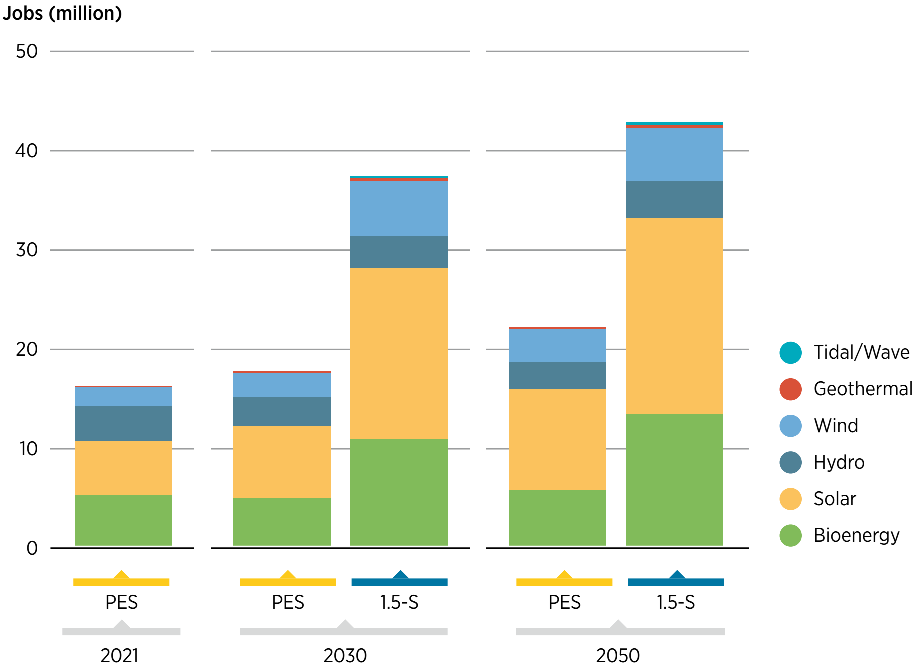
Wind turbine blades are labour intensive to manufacture, but other parts of turbines are less so. Installation resembles the labour intensity of other large construction heavy-infrastructure works. By 2030, the PES creates 2.5 million jobs in wind energy (a 27% increase from 2021), while the 1.5°C Scenario creates 5.6 million jobs (a 182% increase from 2021). Thereafter, the PES maintains similar growth rates in wind energy jobs until reaching 3.4 million jobs by 2050, while the 1.5°C Scenario maintains a rather stable workforce in wind energy through these two decades. By 2050 the 1.5°C Scenario has 2.1 million more wind energy jobs than the PES.

16 SWHs include applications in industry and buildings.

Under the 1.5°C Scenario, jobs relating to SWHs are more prominent in the first decade than in later decades. By 2030 the 1.5°C Scenario has 4.2 million jobs in SWHs; however, by 2050 they decrease to 2.9 million, a consequence of increased electrification of end uses and decreasing labour intensity in the SWH industry. On the other hand, the PES has a lower and stable number of SWH jobs throughout the scenario (around 0.9 million).

Hydropower is one of the oldest renewable energy sources and has grown much less in recent years than other renewables such as wind and solar. Also, new hydro installations increasingly have to be aligned with efforts to protect natural habitats and to minimise social impacts and conflicts surrounding the use of water resources among different communities and countries that share watersheds. Altogether, jobs in hydropower are expected to remain stable at around 3.5 million across the transition.

FIGURE 5.9 Jobs in renewable energy, by technology, in the 1.5°C Scenario and PES (million)



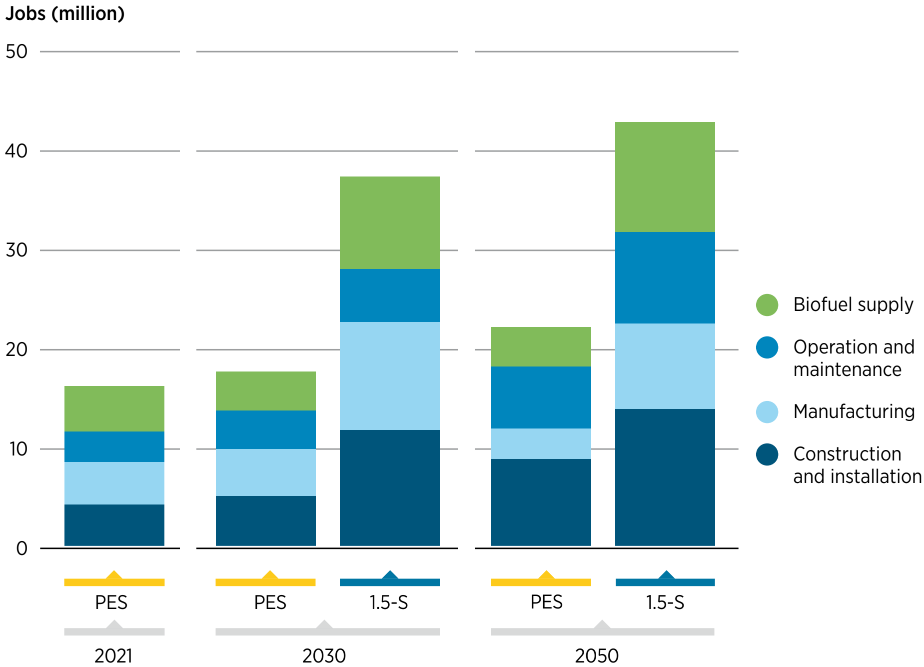
Note: IRENA has been monitoring renewable energy jobs annually since 2011, and resulting data are used to calibrate the macroeconometric model. Once calibrated, the model allows gaps to be filled for places not covered in the annual reviews. This provides a full picture of initial renewable energy employment and its forecasted evolution.

Based on IRENA's analysis.

IRENA's analysis of the different segments of the value chain of renewable energy technologies provides further insights. Jobs in O&M, for instance, are long term and often very stable, increasing in number gradually as capacities expand. Jobs in planning as well as in installation, however, require a consistent, long-term pipeline of projects.

Figure 5.10 presents the evolution of renewable energy jobs for both the PES and 1.5°C Scenario in terms of value chain segments. Construction, installation and manufacturing boost renewable jobs during the next decade in the 1.5°C Scenario, with O&M gaining relative weight as the transition advances. Biofuel feedstock supply jobs also provide an important contribution to 1.5°C Scenario jobs. By 2050, the 43 million jobs in renewable energy under the 1.5°C Scenario are distributed across the value chain with 33% in construction and installation, 26% in biofuel supply, 21% in O&M and 20% in manufacturing.

FIGURE 5.10 Renewable energy jobs, by segment of value chain, in the 1.5°C Scenario and PES



Based on IRENA's analysis.

Jobs by skill level and occupation

Skills matching is an important objective in leveraging the employment benefits from the energy transition. The transition needs skills at all educational levels – primary, secondary and tertiary (Box 5.6). The 1.5°C Scenario involves the following trends: a steady increase of jobs requiring primary education, an initial contraction and later recovery of the number of jobs requiring a secondary education and a sharp peak by 2030 in jobs requiring a tertiary education, which by 2050 decrease to lower numbers than today. Due to inertia in the dynamics of the education system, insights into the future evolution of the labour force's occupational patterns need to be carefully considered to ensure that the appropriate skills are developed as discussed in Chapter 4.

BOX 5.6 Evolution of education levels necessary to support energy transition

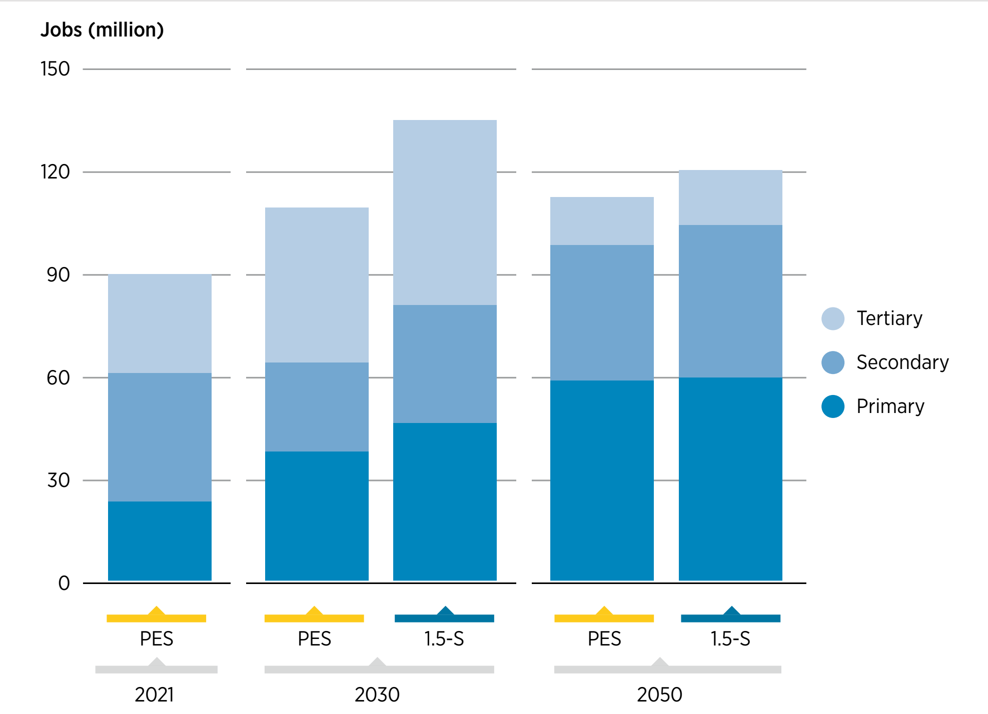
The required skills by economic sector are presented to reflect three groups based on aggregations of the ISCED 2011 classifications per education level:[17] the primary education level comprises ISCED levels 0-2 (childhood, primary and lower secondary education); the secondary education level includes ISCED levels 3-4 (upper secondary, post-secondary non-tertiary education), such as vocational qualifications and specialisations; and the tertiary education level comprises ISCED levels 5-8 (short-cycle tertiary education, bachelor's, master's and doctoral levels). It should be noted however that the level of education and skills are not necessarily correlated: high skills are required by some professional occupations linked to the primary education level, and low skills are sometimes linked to professional occupations associated to the tertiary education level.

Figure 5.11 shows the evolution of education levels necessary to support the energy sector in the PES and 1.5°C Scenario. From 2021, when jobs requiring secondary education dominate (42% of the 91 million energy sector jobs), the first decade sees an increase in the shares of jobs requiring tertiary and primary education. The increase in jobs requiring these education levels is significantly higher in the 1.5°C Scenario than in the PES. In the 1.5°C Scenario, of 137 million energy sector jobs, 40% require tertiary education and 35% primary education by 2030. This shift is driven by the deployment of new energy infrastructure and systems, which mainly takes place in the first decade in the 1.5°C Scenario. On the other hand, by 2030 the number of jobs requiring secondary education declines from current values in both the PES and 1.5°C Scenario. Beyond 2030, there is another significant shift in the structure of the educational requirements needed to support the energy sector: a very sharp reduction in the number of jobs requiring tertiary education, an increase in jobs requiring secondary education and a continuing increase in jobs requiring primary education. In the 1.5°C Scenario, among 122 million energy sector jobs, 13% require tertiary education, 37% secondary education and 50% primary education by 2050.

17 International Standard Classification of Education (ISCED): https://ec.europa.eu/eurostat/statistics-explained/index.php?title=International_Standard_Classification_of_Education_(ISCED).

Education requirements will evolve through the energy transition.

FIGURE 5.11 Evolution of the distribution of jobs in the energy sector, by education level, in the PES and 1.5°C Scenario



Based on IRENA's analysis.

Coordination between the energy and educations sector is required to fulfill future skills demand.

The trends in the educational requirements of the energy sector call for better co-ordination between the sector and educational institutions. The 2030 boom in tertiary education requirements, as discussed above, is likely to encourage people to continue to seek such qualifications even though jobs requiring their educational profiles will materialise in lower numbers. An integrated approach to labour and educational policy and planning will be needed to address this challenge, and also to better integrate the educational requirements in the energy sector with those of other sectors. Part of the answer will lie with efforts to better anticipate emerging trends that influence education levels and specialisations. Another aspect concerns identifying transversal skills, *i.e.*, skills that are not exclusively related to a particular job or task but rather are applicable to a wide variety of work settings and roles. For example, organisational or inter-personal skills fall under this category.[18]

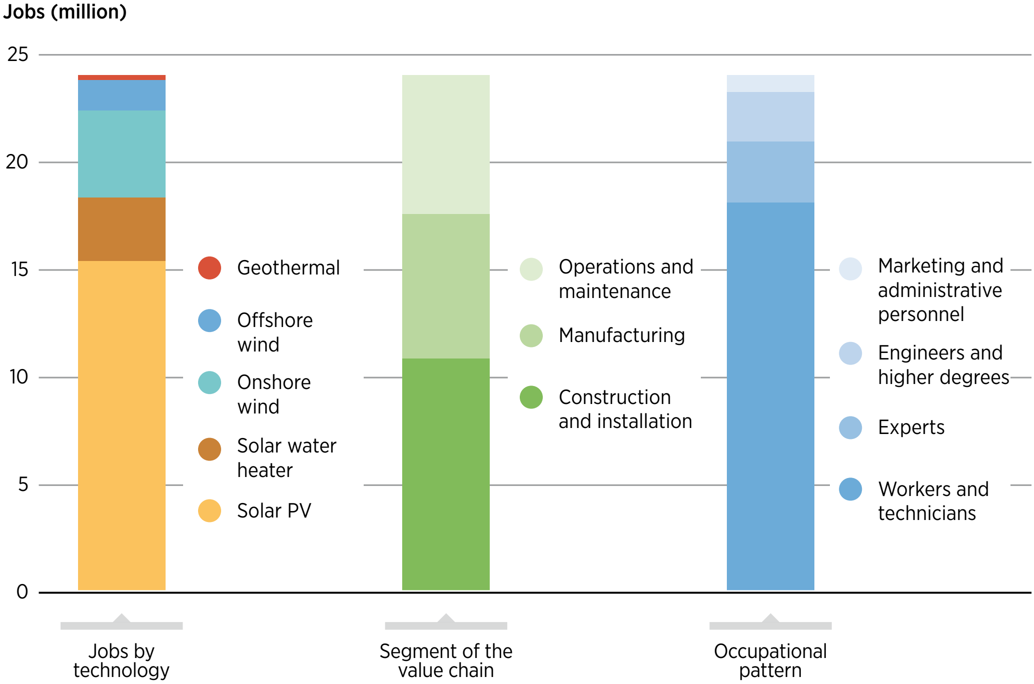
In addition to future educational requirements of the workforce needed to support the transition, analysis of specific occupations is essential. To illustrate this point, Figure 5.12 provides insights for a subset[19] of renewable technologies by 2050, showing the structure of the required jobs by technology, segment of value chain and occupational requirements. Construction and installation dominate the segments of the value chain accounting for 45% of the jobs. In terms of occupational requirements, workers and technicians represent the largest share with 76% of the total.

The results presented in this section show that the energy transition offers significantly more job opportunities than those that are lost. Indeed, by 2030 when moving from the PES to the 1.5°C Scenario 14 million jobs are lost in fossil fuels, but 40 million jobs are gained in transition-related technologies. By 2050 the difference between the PES and 1.5°C Scenario is a loss of 20 million jobs in fossil fuels and a gain of 28 million jobs in transition-related technologies.

18 Ideally, this is done in such a way that people with different educational levels can more readily acquire the skills needed for the occupations that society requires, while finding satisfaction in their professional life. This requires increased flexibility in the way in which the links between education and work life are organised and understood by society.

19 These technologies are PV, SWH, onshore wind, offshore wind and geothermal. The analysis draws from IRENA's work on leveraging local capacities (IRENA, forthcoming-c, 2018d, 2017e, 2017f). The skill structure for additional technologies can be fleshed out as the leveraging analysis for those technologies becomes available.

FIGURE 5.12 Structure of jobs in the 1.5°C Scenario by 2050 for a subset of renewable technologies by technology, segment of value chain and occupational requirements



Note: O&M = operation and maintenance; PV = photovoltaic; SWH = solar water heater.
Based on IRENA's analysis.

IRENA's analysis offers insights into the types of jobs needed to support the transition by technology, segment of the value chain and educational and occupational requirements. These are crucial elements to inform the transition's policy framework. But beyond that, policy needs to address upfront the potential job misalignments (temporal, educational, geographic) that may arise. Job opportunities due to the energy transition occur where installations of renewable energy systems are located, where relevant technologies (and their inputs along the supply chain) are produced and where related infrastructure is enhanced. Fossil fuel jobs are often located in other parts of a country and workers may be reluctant to move or face barriers to do so. Skills and qualifications needed for the energy transition are not readily available; even where they are, additional licensing is often required. These misalignments need to be addressed by a policy framework as outlined in Chapter 4.

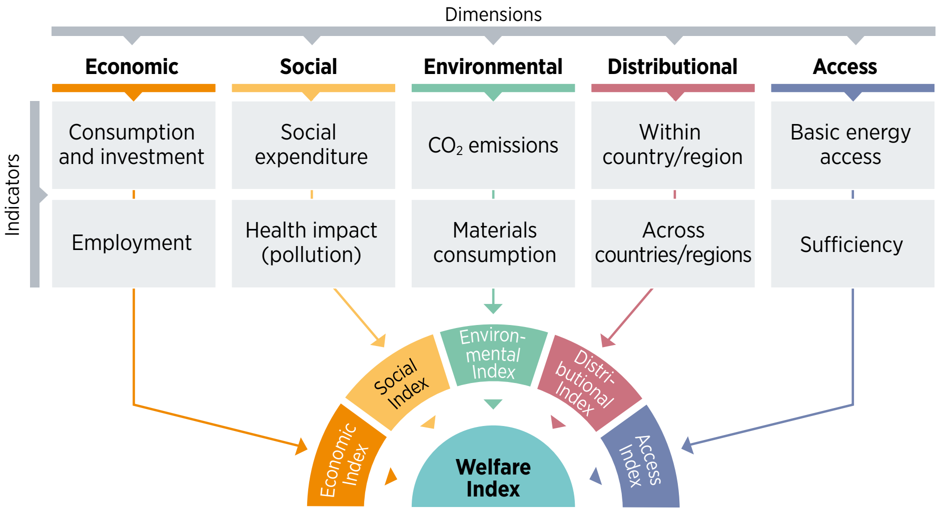
5.2.3 Energy Transition Welfare Index

This sub-section first presents IRENA's Energy Transition Welfare Index and discusses the welfare results for both the PES and 1.5°C Scenario.

Prosperity and people's well-being have many aspects and dimensions. IRENA's Energy Transition Welfare Index captures five dimensions, namely, economic, social, environmental, distributional and energy access (see Figure 5.13). Measuring the energy transition's impact across these dimensions provides a quantitative basis to inform transition roadmaps to reaping all the potential socio-economic and environmental benefits. The Energy Transition Welfare Index allows a comparison between scenarios both in overall terms and along each of the five different dimensions.

The Energy Transition Welfare Index and its dimensional indexes are defined in absolute and normalised terms for each scenario, which allows for direct comparison between scenarios. However, as for other socio-economic footprint results (GDP, employment), the relative performance of one scenario against another (1.5°C Scenario relative to the PES) may also be of interest. This section presents both absolute and relative welfare results.

FIGURE 5.13 Structure of IRENA's Energy Transition Welfare Index



20 IRENA's Energy Transition Welfare Index includes five dimensions which provide an adequate balance between the multi-dimensional characteristics of prosperity/well-being and synthesise requirements for useful insights. Each dimension of IRENA's Energy Transition Welfare Index includes two indicators. These indicators are combined into a dimension's index, and the different dimensional indexes are finally combined into the overall welfare index (see Figure 5.13 and Annex 5.2) that allows an overall welfare rating of each transition roadmap. All indexes are normalised so that they score between 0 and 1. The higher the value of an index, the greater its contribution to welfare. Indexes are combined by using a modified geometric mean (see Annex 5.2 for methodology).

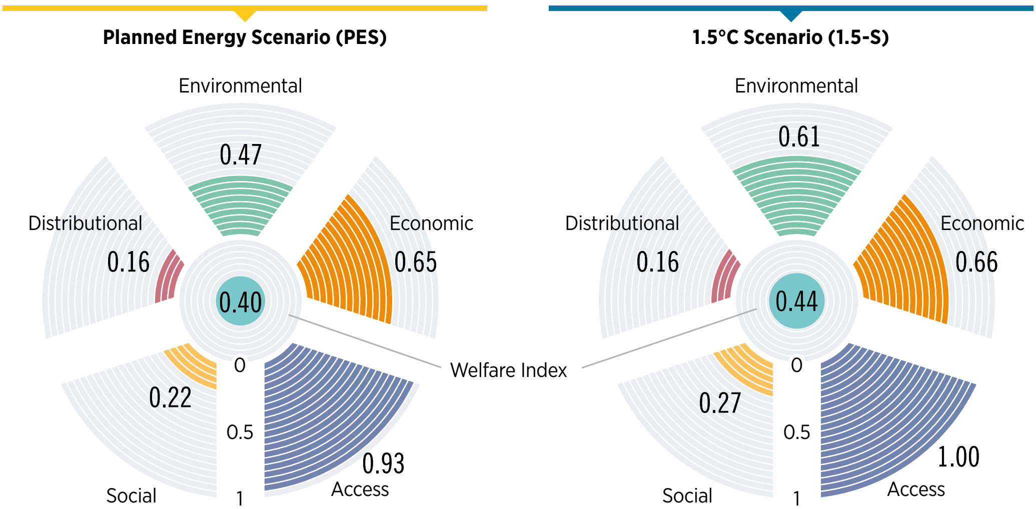
Welfare results for PES and 1.5°C Scenario: Global

There are two ways of presenting IRENA's Energy Transition Welfare Index: a multi-dimensional representation of welfare gains in its different dimensions, and a unidimensional representation that groups together the contributions from each of the dimensions. For all indexes, values range from zero (the worst possible outcome) to one (the best outcome).

Figures 5.14 and 5.15 present global results for the year 2050. Welfare improves over time in both scenarios but is higher under the 1.5°C Scenario than under the PES. By 2030, the Energy Transition Welfare Index value is 0.25 for the PES and 0.34 for the 1.5°C Scenario; by 2050, it is 0.40 and 0.44, respectively. The Difference between the 1.5°C Scenario and PES is mostly due to the environmental, access and social dimensions, in decreasing order. The dimensions with the highest index values are access (with full access to modern energy already reached by 2030 for the 1.5°C Scenario), economic and environmental, while the social and distributional dimensions have low index values in both the PES and 1.5°C Scenario. See Annex 5.3 for data tables.

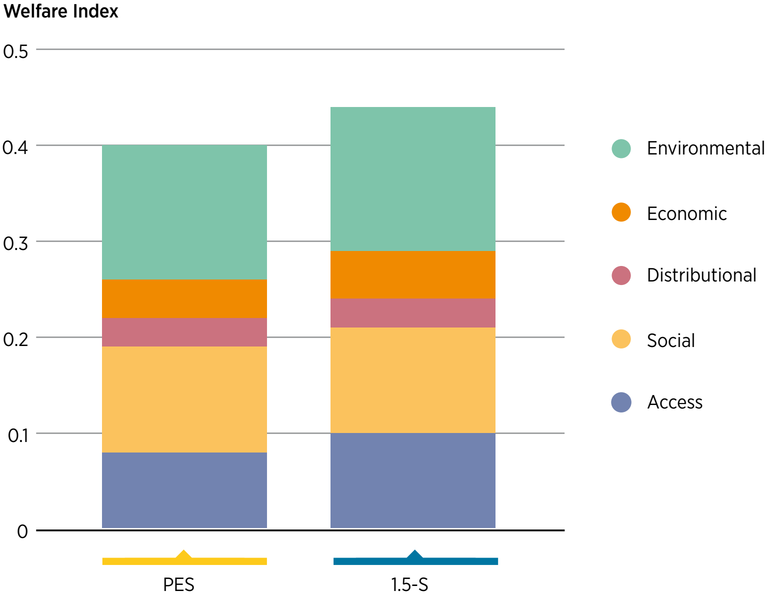
In both scenarios, the low values of the social and distributional dimensions drag the overall Energy Transition Welfare Index down. These two dimensions have not received much attention in policy circles to date, though awareness of the crucial role they can play as enablers or barriers is now increasing.

FIGURE 5.14 Overall welfare (centre) and dimensional (blades) indices for the PES and 1.5°C Scenario by 2050, global results, multi-dimensional representation



Note: In the multi-dimensional representation of the Energy Transition Welfare Index that resembles a wind turbine rotor (nacelle and blades), the nacelle documents the overall welfare index with a concentric circle. Each of the five rotor blades represents one of the dimensional indices, indicating the respective index values.

FIGURE 5.15 Overall Energy Transition Welfare Index and dimensional contributions of the PES and 1.5°C Scenario by 2050, global results, unidimensional representation



Note: In the unidimensional representation of the Energy Transition Welfare Index, the total height of the stacked bar represents the overall welfare index (the same value as shown in the nacelles of Figure 5.14), and each of the segments represents the contribution to the total value from the different welfare dimensions.

Based on IRENA's analysis.

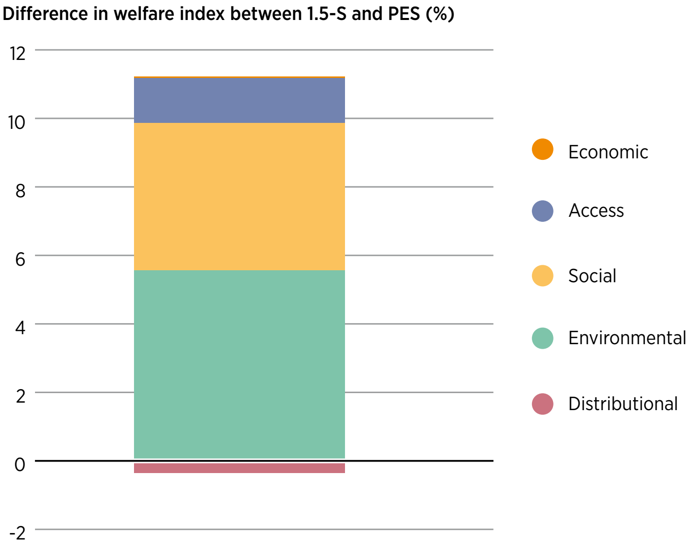
Relative welfare results of 1.5°C Scenario and the PES

As was done for the other socio-economic indicators (GDP, employment), the relative welfare index measures the difference between the 1.5°C Scenario and PES results. By 2050, the overall welfare index improves by 11% with the environmental, social and access dimensions being the main contributors to this improvement, as illustrated in Figure 16.

It is worth noting how the role of the social and access dimensions is reversed compared to the absolute index values: The access dimension is the main contributor to the absolute welfare index because it reaches very high dimensional index values (1 for 1.5°C Scenario). However, since its improvement from the PES to 1.5°C Scenario is not very high[21] at the global level, in relative terms it makes a modest contribution. Conversely, the social dimension makes a modest contribution to the absolute welfare index, but in comparative terms between the two scenarios is the second-most important after the environmental dimension (Figure 5.16).

21 Under both the PES and 1.5°C Scenario, the energy sufficiency threshold is achieved at the global level.

FIGURE 5.16 Relative improvement of the Energy Transition Welfare Index and its dimensional contributions by 2050, global results



Based on IRENA's analysis.

Welfare results: By dimension

As explained earlier, each dimension of the Energy Transition Welfare Index is informed by two indicators.[22] This section discusses how the respective indicators influence the dimensional index during the transition.

Economic dimension

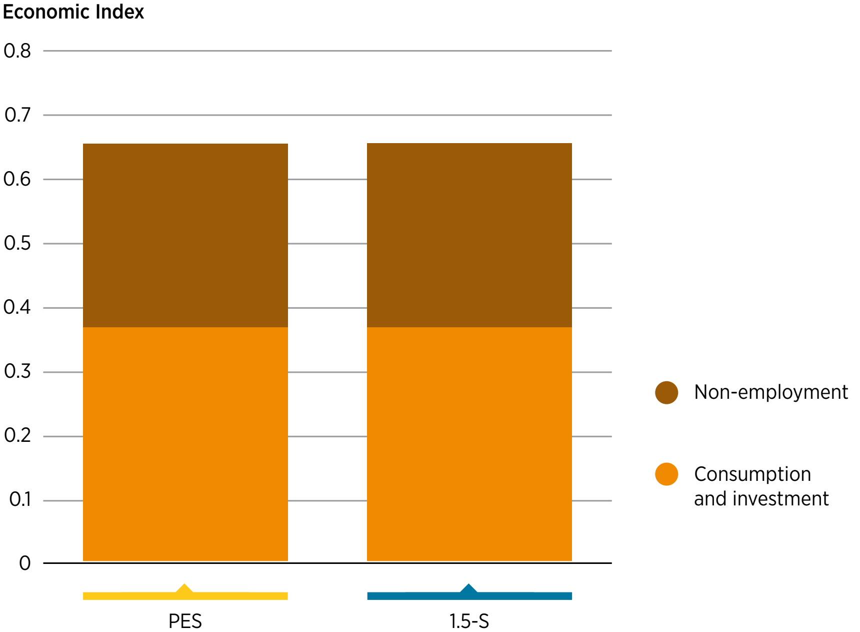
The economic index is very similar for both the PES and 1.5°C Scenario (0.65 and 0.66, respectively, by 2050), reflecting the energy sector's relatively small share of the overall economy and labour force. Both indicators in this dimension contribute similarly to the dimension's index (Figure 5.17), with the energy transition leading to slight improvements in both consumption and investment and in non-employment.

22 The distributional dimension includes four indicators, combined into two sub-indexes by taking the average of the income and wealth components.

That said, the improvement between the PES and 1.5°C Scenario is more pronounced during the first decade (reaching a 1% difference around 2025), mainly due to front-loaded investments in the 1.5°C Scenario.

The economic index, for both the PES and 1.5°C Scenario, presents a minimum value shortly after 2030, resulting from the balance of two opposing trends: the consumption and investment index steadily increases with aggregated economic activity (GDP) while the non-employment index decreases with time, resulting from the balance of demographic and labour dynamics, including productivity improvements.[23]

FIGURE 5.17 **Economic index under the 1.5°C Scenario and PES by 2050, by indicator, global results**



Based on IRENA's analysis.

23 It should be noted here that although the socio-economic modelling captures econometric labour productivity improvements, it does not fully address current megatrends such as the disruptive impacts of artificial intelligence and automation. Hence, the decrease of the non-employment index (increase of non-employment) could be steeper than the analysis shows.

At the global level, per capita consumption and investment evolves from about USD (2019) 8 500 per annum by 2021 to around USD (2019) 17 000 per annum by 2050, still far from the sufficiency limit introduced in this indicator's index (USD [2019] 45 000 per annum). Of course, country and regional disparities in this indicator are substantial, as partly documented by the distributional dimension below.

Global non-employment[24] changes from around 17% by 2021 to 31% by 2050, for both the PES and 1.5°C Scenario. This growing non-employment, due to the demographic and labour dynamics, is not a consequence of the transition, but of the context within which the transition is currently progressing. It highlights the need to holistically address contextual elements that go well beyond the technical aspects of the energy transition as noted in Chapter 4.

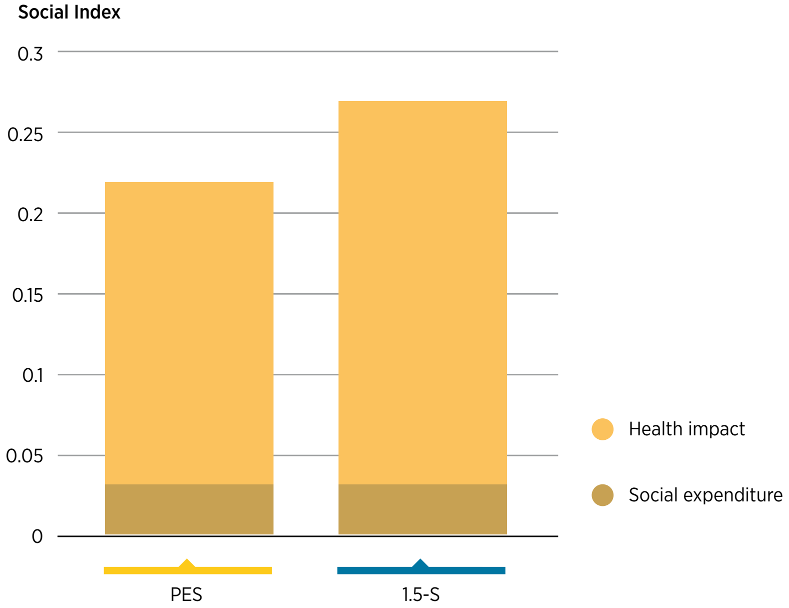
Social dimension

The social index improves with time in both the PES and 1.5°C Scenario. By 2050 it reaches a value of 0.22 for the PES and 0.27 for the 1.5°C Scenario (a 23% improvement of the 1.5°C Scenario over the PES) (Figure 5.18). However, these values are low even to 2050, indicating that there is significant room for improving welfare outcomes by addressing the social dimension. The health impact indicator dominates as outdoor and indoor air pollution improves, with the social expenditure indicator providing a much smaller contribution. Hence, there is significant room to improve the Energy Transition Welfare Index by increasing social spending.

IRENA's 1.5°C Scenario leads to improvements in both social indicators. Health improvements are a direct consequence of phasing out the combustion of fossil fuels and transitioning away from traditional fuels for cooking. The policy basket implemented with the 1.5°C Scenario also addresses the improvement of the social spending indicator through different channels, including increased public participation by earmarking public fiscal resources to energy transition requirements through both direct investment and subsidies, public spending for a just and equitable transition (including international co-operation) and an increase in general social spending over the PES.

24 Share of working age population (age group from 15 to 64 years) without paid employment and not belonging to youth (14-24 age group) undertaking education.

FIGURE 5.18 Social index under the 1.5°C Scenario and PES by 2050, by indicator, global results



Based on IRENA's analysis.

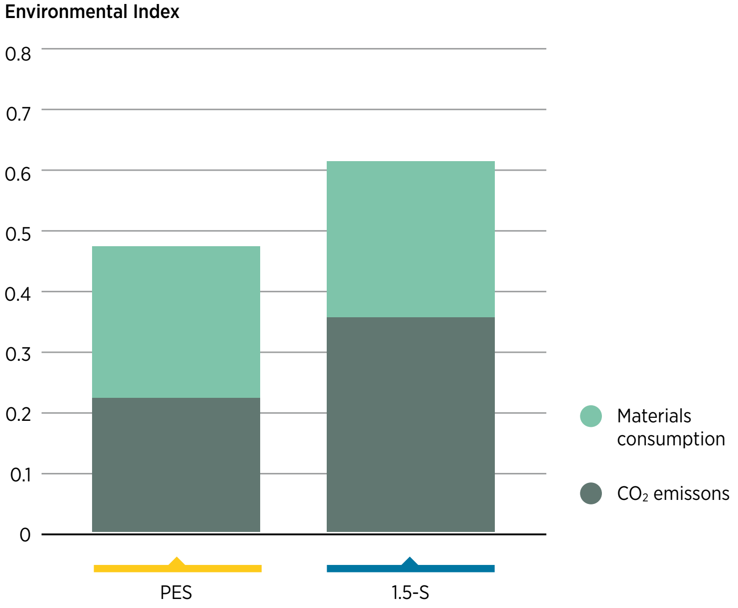
Environmental dimension

The environmental index by 2050 is 0.47 for the PES and 0.61 for the 1.5°C Scenario (a 30% improvement of the 1.5°C Scenario over the PES). Both indicators contribute significantly to the environmental index in both the PES and 1.5°C Scenario, but the CO_2 emissions indicator is the one that drives the improvement of the 1.5°C Scenario over the PES (Figure 5.19). The index deteriorates over time as a consequence of the increase in materials consumption.

Both scenarios have similar values of the materials consumption indicator (per capita materials consumption)[25] evolving from 5.7 tonnes/person-year by 2021 to 7.5 tonnes/person-year by 2050. This reflects that the energy transition alone cannot resolve significant, parallel challenges, such as bringing global material consumption down to sustainable levels – neither for materials used by the energy industry, nor for materials used for non-energy value chain production.

25 This makes reference to domestic material consumption excluding fossil fuels, and hence includes the aggregate consumption of non-metallic minerals, metal ores and biomass. It should be noted that this aggregate measure of materials consumption, although an adequate proxy for the sustainability implications of materials use, does not provide the resolution needed to track the consumption of potentially scarce materials in relation to available resources.

FIGURE 5.19 Environmental index under the 1.5°C Scenario and PES by 2050, by indicator, global results



Based on IRENA's analysis.

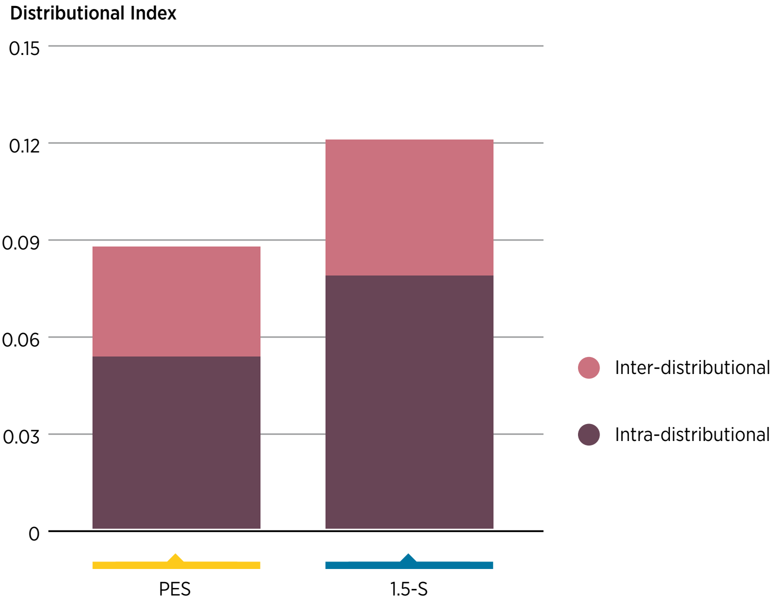
Distributional dimension

The distributional dimension is increasingly recognised as key to enabling the energy transition. IRENA has for the first time introduced this dimension in its welfare indicator, with the goal of generating insights that contribute to fostering a just and inclusive energy transition. While GDP grows and the implemented policy basket leads to an improved distribution, the index itself remains low, indicating potential barriers to the energy transition from an equity point of view. The distribution of benefits is not uniform across countries and income groups, implying the transition does not by itself resolve income and wealth inequalities. Distributional results are presented here as a global aggregate. IRENA's future work will further examine regional differences.

Dedicated policies are needed to address distributional challenges.

The distributional impact of the energy transition depends on the energy transition roadmaps and the policy baskets used to implement them. Dedicated policies are, therefore, needed to address distributional challenges. The climate policy basket implemented under the 1.5°C Scenario includes progressive government revenue recycling through lump-sum payments, direct public involvement in more equitable distribution of benefits from the transition, increased social expenditure, differentiated carbon pricing that limits the direct burden on citizens and international collaboration with a focus on justice and equity.

FIGURE 5.20 **Distributional index under the 1.5°C Scenario and PES Average 2021-2050, by indicator, global results**



Based on IRENA's analysis.

The 1.5°C Scenario has positive distributional impacts with targeted measures.

The combination of the 1.5°C Scenario energy transition roadmap and the accompanying policy framework brings about a 37% improvement in the average distributional index over the PES during the transition period, with both the intra- and inter-distributional components contributing (Figure 5.20). The 1.5°C Scenario produces an average improvement of 44% in the intra-distributional sub-dimension[26] and 20% in the inter-distributional sub-dimension.

The inter-distributional indicator, which measures changes to inequalities between countries, significantly improves over time, moving from an almost zero index by 2021 to reach about 0.16 by 2050, with both its wealth and income components improving over time (with wealth reaching an index of about 0.14 and income of about 0.20). However, these values indicate that inequality between countries is still very high by 2050.[27]

There are many dynamics at play influencing the inter-distributional indicator, making it more complex to explore than the aggregate impacts on economic activity (GDP). International co-operation as included in the 1.5°C Scenario climate policy basket[28] significantly reduces inter-inequality during the first years of the transition but its impact fades with time because of the underlying aggregated economic growth.[29] Raising the sums mobilised through international climate co-operation beyond the USD 300 billion/year assumed on average for the 1.5°C Scenario could achieve greater distributional benefits.

26 For the global results herewith presented, the intra-distributional component measures inequality in the distribution of income and wealth across the global population (global citizens).

27 The corresponding indicator values, wealth quintile ratios (WQR) and income quintile ratios (IQR), are about WQR = 35 and IQR = 16 by 2050.

28 In cumulative terms, the assumed international co-operation policies amount to a cumulative spending of USD 8.6 trillion, representing an average of just below USD 300 billion/year. All countries contribute to these funds as per their capabilities and responsibilities, and the funds are distributed as per the country's human development, fossil fuel vulnerability and equity in the distribution of the mitigation effort.

29 Note that the underlying aggregated economic activity (GDP) for the 1.5°C Scenario has a compound annual growth rate of 3% between 2021 and 2050. Hence, the weight of the international co-operation monetary flows relative to aggregated economic activity significantly reduces with time.

The transition process itself can, if not properly addressed with a focused policy framework, trigger inequality increases in several ways. While the economic benefits of the transition are rather distributed, its negative impacts associated to fossil fuel dependence and vulnerability are far more concentrated. Further, a front-loaded transition investment meant to speed up mitigation while addressing the recovery needs from the COVID-19 crisis may trigger inflationary and price effects[30] that could have a stronger impact in poor countries. Advanced economies, due to their structure, diversity and international positioning, are able to reap more benefits from the energy transition investment stimulus. Properly addressing these challenges and redirecting the transition so that it improves the distributional dimension requires a holistic policy framework with a clear focus on distributional issues.

The intra-distributional indicator presented here makes reference to the global population. The intra-distribution index improves significantly over time, evolving from 0.01 in 2020 to 0.16 by 2050. The lump-sum payments to recirculate government revenue surplus play a significant role in the 1.5°C Scenario over the PES improvement for this index, with the difference between both scenarios reaching a maximum of about 100% around 2030. The two components from this index (income and wealth) have very different contributions: the income component for the 1.5°C Scenario reaches index values as high as 0.40 from 2030 onwards, while the PES barely reaches 0.30 towards the end of the transition.[31] But it is the wealth component that drags the intra-distributional indicator down, with extremely high wealth quintile ratios (WQRs) producing a zero value of the associated index.

Access dimension

A discussion of welfare under the energy transition would be incomplete without addressing the energy access deficit faced by a significant proportion of the world's population. Over 755 million people lived without electricity access in 2019 (IEA *et al.*, 2021), and 3.5 billion received unreliable supply (Ayaburi *et al.*, 2020). Further, 2.6 billion relied on traditional fuels for cooking (IEA *et al.*, 2021). The lack of access to modern energy services significantly affects households' access to resources and income-generating opportunities and constrains economic and industrial activity. Access to modern energy services is closely linked to access to essential public services such as health care and education, and improves overall well-being and safety, particularly for women and children. Energy equity and distributive justice – *i.e.*, the right to affordable and accessible energy – is increasingly recognised as a critical pillar of a just energy transition (Sovacool and Dworkin, 2015; World Energy Council, 2020; Müller *et al.*, 2020).

30 Inflationary effects may stem from the investment stimulus triggering an increase in general prices. Interest rates could also increase if there is an increase in demand for loans to address the transition's investment needs. Energy prices could increase because of the costs of deploying the new generating and flexibility capacity and infrastructure, with direct and indirect effects on general prices. From 2030 onwards, the 1.5°C Scenario inflationary effects fade in many countries and there is a marked trend to reduce income inequality in both the PES and 1.5°C Scenario. However, the 1.5°C Scenario reduction is slower because rich countries keep on being able to reap more economic benefits from the transition than poor countries.

31 Income quintile ratios are still high at the end of the transition (IQR = 55), indicating room for further improvement in this indicator.

Estimates suggest that by 2030 – the target year to reach universal modern energy access under Sustainable Development Goal 7 – 660 million people will still be without electricity access and 2.3 billion will continue to rely on traditional fuels (Müller *et al.*, 2020). Stepping up to the 1.5°C Pathway must thus happen in tandem with efforts to scale up sustainable modern energy access. Tackling inequalities in energy access and consumption also provides the foundation for a more resilient and inclusive society by catalysing economies, creating jobs, strengthening livelihoods and improving well-being for all.

The socio-economic impacts of gaining access to modern energy can be transformative in many respects for communities and enterprises. Energy access has cross-cutting impacts across several welfare dimensions discussed earlier in this chapter, namely economic (through higher incomes, consumption and employment), social (through lower health impacts of traditional fuels) and distributional. However, its effects across other dimensions are strongly diluted by scale effects. For instance, the increase of consumption and investment brought about by energy access affects the lower region of the income distribution, and hence will have a negligible impact on average consumption and investment triggered by the energy transition.

Within the access dimension of the Energy Transition Welfare Index, the access itself counts (*i.e.*, share of the population with access) as well as its sufficiency over time (*i.e.*, progression along the energy ladder). The use of both indicators concurrently enables a discussion beyond the achievement of universal access by 2030 (defined usually in binary terms) and addresses inequalities in consumption across regions and accounts for opportunities to link energy access with income-generating services that generate strong socio-economic dividends over the long term (see Box 5.7).

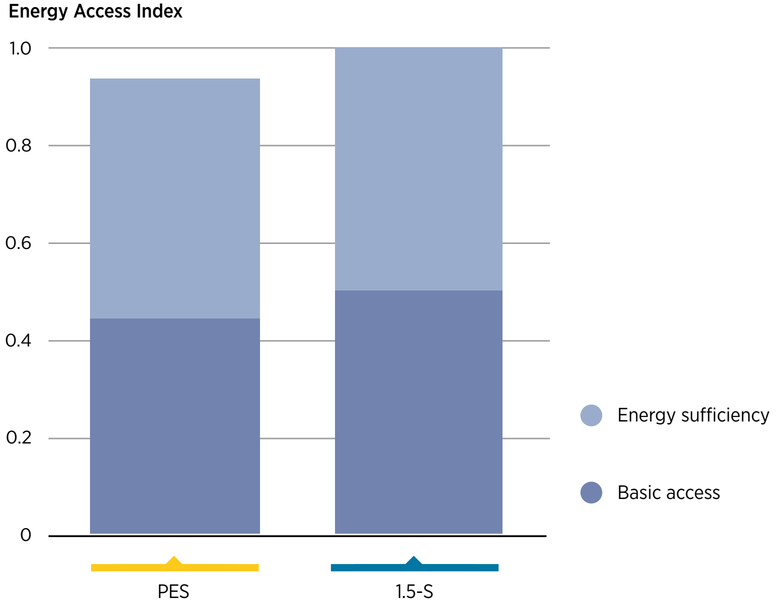
Sufficiency is measured as per capita total final energy consumption to capture all energy needs holistically. A limit is set based on distributional and convergence considerations, energy sufficiency literature and energy efficiency (see Annex 5.2 for detailed methodology). Once universal access and sufficiency limits are reached, the dimension becomes neutral for the Energy Transition Welfare Index with impacts now fully captured within other dimensions.

At the global level, by 2050, the access index is 0.93 for the PES and 1 for the 1.5°C Scenario (a 7% improvement of the 1.5°C Scenario over the PES) (Figure 5.21). This improvement is driven by the basic energy access indicator, whose index is 0.87 for the PES and 1 for the 1.5°C Scenario (a 14.6% improvement of the 1.5°C Scenario over the PES).[32] The energy sufficiency indicator is, at a global level, 1 for both the 1.5°C Scenario and PES along the scenarios' time span.

Tackling inequalities in energy access and consumption advances a more resilient society.

32 The 1.5°C Scenario reaches full basic energy access by 2030, in line with the Sustainable Development Goals. By 2030 the improvement of the 1.5°C Scenario over the PES in the basic energy access index is 36.1%, and in the overall access index 16.6%. From 2030 onwards the difference between the 1.5°C Scenario and PES diminishes with time since the 1.5°C Scenario has already reached full access and the PES is still progressing in the basic access dimension.

FIGURE 5.21 Contributions to two access index indicators under the 1.5°C Scenario and PES by 2050, global results



Based on IRENA's analysis.

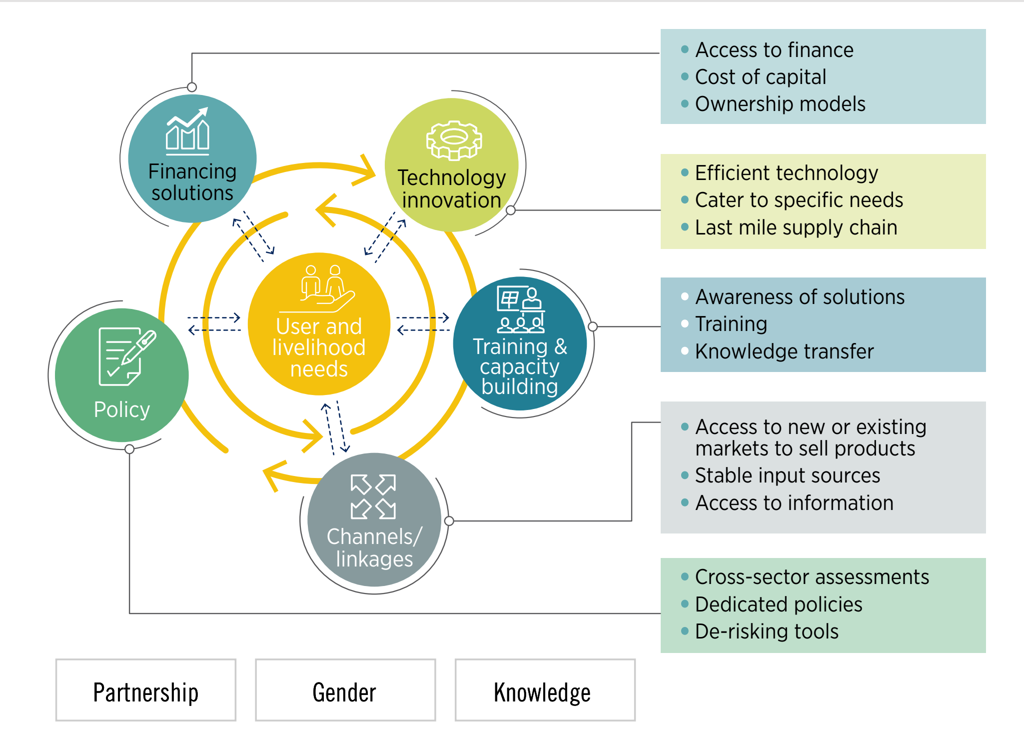
At a global level, both the 1.5°C Scenario and PES are above the sufficiency level of per capita total final energy consumption (20 kilowatt hour per day, kWh/p-d). Hence, both scenarios reach the highest possible value for the sub-index of energy access sufficiency. However, global averages hide large country and regional inequalities in terms of total final energy consumption, with some countries reaching per capita consumption levels nearly ten times higher than the sufficiency level.

BOX 5.7 Linking energy supply with livelihood services

Traditional approaches to energy access have focused on achieving a certain number of connections or deploying a given number of systems. The need to encourage productive end uses and to link them with livelihoods is often an afterthought. An alternative approach is to identify energy needs that, if met, are likely to transform people's livelihoods across sectors by increasing productivity and incomes, enhancing value creation and access to markets, reducing drudgery and offering a pathway towards long-term social security.

Decentralised renewable energy solutions are particularly well equipped to provide tailored energy services for livelihood activities across sectors. There are critical differences between an approach that is technology centric (*i.e.*, it aims to accelerate the deployment of specific solutions such as mini-grids and solar home systems) and one that is end-user/livelihood centric (defines technology solutions based on identified energy needs across value chains). The ecosystem for livelihoods assumes additional dimensions (market linkages, sector-specific skills upgrades, couplings of energy technology with efficient livelihood equipment), which in turn maximise the value of improved energy access (Figure 5.22).

FIGURE 5.22 Ecosystem needs for supporting livelihoods with distributed renewable energy solutions

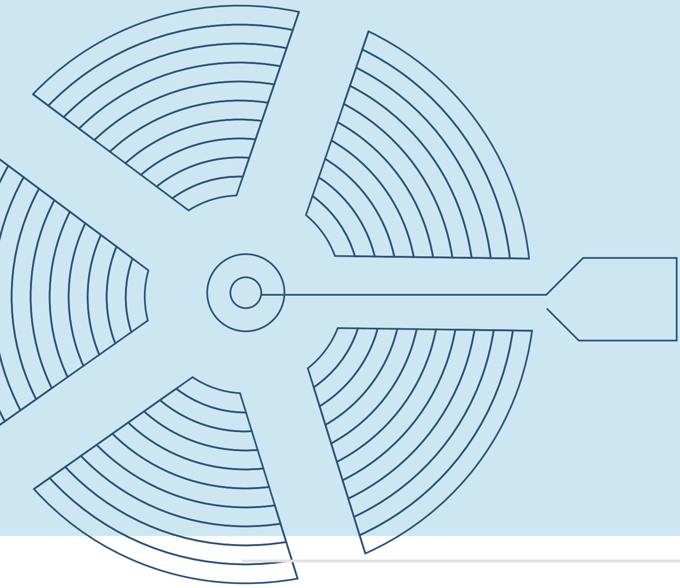


Source: SELCO Foundation and IRENA

5.3 CONCLUSION

The analysis of global socio-economic impacts presented in this chapter indicates that the world will be better off – in multiple dimensions – if societies take the 1.5°C Scenario route. Spurred by investments across the many avenues of the energy transition, global GDP will receive a boost of an average of 1.2% to 2050 over PES. Even in the case of negative impact on GDP due to climate damages, the 1.5°C Scenario is a compelling option as the counterfactual would be much worse. Throughout the transition period, economy-wide employment is 0.9% higher on average in the 1.5°C Scenario compared to PES. The energy sector will have at least 122 million jobs in 2050, with renewable energy jobs rising from more than 11.5 million today to 43 million in 2050. Meanwhile, all welfare dimensions analysed – economic, social, environmental, distributional and access – fare better under the 1.5°C Scenario, offering a 11% improvement in the overall Energy Transition Welfare Index over the PES.

Socio-economic impacts may vary at the regional or country level compared to the global results presented here. Future IRENA work will document the socio-economic footprint of the 1.5°C Scenario at the regional and country level. The socio-economic footprint analysis highlights how energy transition roadmaps are closely linked with the holistic policy framework, with links becoming stronger as ambitions align with the 1.5°C Pathway. Still navigating the COVID-19 pandemic and with increasing climate change impacts already being felt all over the world, the current situation calls for a holistic analysis that explores transition roadmaps and policy frameworks on an integrated and equal basis. In this report IRENA has advanced such analyses by closely integrating the policy dimension in the macroeconometric modelling with a focus on addressing social challenges.



A **WAY FORWARD**

Less than a decade is left to achieve the 2030 Agenda for Sustainable Development and secure a fighting chance for a 1.5-degree world. The stakes cannot be higher, and how the energy system evolves in the coming years will define our shared future. IRENA's World Energy Transitions Outlook provides a realistic pathway that can make a difference in the limited time available. It draws on the existing technology solutions to rapidly progress and offers transparent choices for a different energy future.

The Outlook emphasises that investment in a comprehensive transformation involves not just a mix of technologies but also investment in the policy package to put them in place and optimise their economic and social impact. It clearly shows that a 1.5-degree world requires wide-reaching action across multiple dimensions to maximise benefits and carefully manage adverse effects. But it also indicates that a renewables-based energy transition can be a powerful equaliser in the world where disparities and gaps between communities, nations and regions continue to widen.

While ambitious climate and energy targets continue to be set, many are yet to be translated into effective policy and regulatory frameworks. Renewable technologies have yet to make sufficient inroads into the end-use sectors, such as direct heat, buildings and transport. And countries are grappling with multiple priorities, many of which cannot be solved in isolation. The need for international cooperation is evident as the world looks for solutions to meet energy and economic demands, rectify systemic inequalities, and reverse the climate change trends.

The technology avenues, investments and policies proposed in this Outlook can take us closer to where we need to be. There will be innovations, developments, and breakthroughs on the way, but we must not wait. Because we have no time to lose.

References

Ambrose, J. (2019), "World's biggest sovereign wealth fund to ditch fossil fuels", 12 June, The Guardian, www.theguardian.com/business/2019/jun/12/worlds-biggest-sovereign-wealth-fund-to-ditch-fossil-fuels.

Andersson, J. and G. Atkinson (2020), "The distributional effects of a carbon tax: The role of income inequality", *Centre for Climate Change Economics and Policy*, Working Paper 378, and *Grantham Research Institute on Climate Change and the Environment*, Working Paper 349, London School of Economics and Political Science, London.

Appunn, K. (2021), "Three more German coal power plants to go offline in December 2021", www.cleanenergywire.org/news/three-more-german-coal-power-plants-go-offline-december-2021#:~:text=Two%20German%20hard%20coal%20power,the%20second%20round%20of%20auctions.

Ashden (2021), "Ashden awards longlist highlights global climate solutions", https://ashden.org/news/ashden-awards-longlists-highlight-global-climate-solutions/.

Ayaburi, J., M. Bazilian, J. Kincer and T. Moss (2020), "Measuring 'reasonably reliable' access to electricity services", *The Electricity Journal*, Vol. 33, no. 7, 106828, https://doi.org/10.1016/j.tej.2020.106828.

Beck, M.R., N. Rivers, R. Wigle, H. Yonezawa, (2015), "Carbon tax and revenue recycling: Impacts on households in British Columbia", *Resource and Energy Economics*, Vol. 41, pp. 40–69.

Bellini, E. (2020), "Portugal's second PV auction draws world record low bid of $0.0132/kWh", *PV Magazine*, 24 August, www.pv-magazine.com/2020/08/24/portugals-second-pv-auction-draws-world-record-low-bid-of-0-0132-kwh/ (accessed 26 June 2021).

Beyond Coal (2021), "Coal exit tracker", https://beyond-coal.eu/coal-exit-tracker/ (accessed 26 June 2021).

BNEF (2021a), *Energy Transition Investment Trends*, Bloomberg New Energy Finance, London.

BNEF (2021b), *Corporate clean energy buying grew 18% in 2020*, despite mountain of adversity, https://about.bnef.com/blog/corporate-clean-energy-buying-grew-18-in-2020-despite-mountain-of-adversity/ (accessed 26 June 2021).

BP (2018), "Energy Outlook: 2020 edition", *BP – British Petroleum*, www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/energy-outlook/bp-energy-outlook-2020.pdf.

Brookings (2021), "The case for US cooperation with India on a just transition away from coal", www.brookings.edu/research/the-case-for-us-cooperation-with-india-on-a-just-transition-away-from-coal/.

Bundesnetzagentur (German Federal Network Agency) (2021), "Power plant list of the Federal Network Agency – as of January 19, 2021", www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/Versorgungssicherheit/Erzeugungskapazitaeten/Kraftwerksliste/Kraftwerksliste_2021_1.html;jsessionid=B825E015134CF318D6E1B2B956C7A9EF?nn=320094.

Burke, M. and V. Tanutama (2019), "Climatic constraints on aggregate economic output", Working paper no. 25779, *National Bureau of Economic Research*, Cambridge, www.nber.org/papers/w25779.

Burke, M., S.M. Hsiang and E. Miguel (2015), "Global non-linear effect of temperature on economic production", *Nature*, Vol. 527, pp. 235–239.

Burke M., W.M. Davis and N.S. Diffenbaugh (2018), "Large potential reduction in economic damages under UN mitigation targets", *Nature*, Vol. 557, pp. 549–553.

Business Day (2020), "Denmark gets nearly 50% of its electricity from wind power", *Business Day*, 2 January 2020, www.businesslive.co.za/bd/world/europe/2020-01-02-denmark-gets-nearly-50-of-its-electricity-from-wind-power/ (accessed 26 June 2021).

CAN (2020), "Energy transition in the Western Balkans: 2020 missed opportunities", *Climate Action* Network, https://caneurope.org/energy-transition-western-balkans-2020-missed-opportunities/.

Canada's Ecofiscal Commission (2016), *Choose Wisely: Options and Trade-Offs in Recycling Carbon Pricing Revenues*, Canada's Ecofiscal Commission, Montreal, https://ecofiscal.ca/wp-content/uploads/2016/04/Ecofiscal-Commission-Choose-Wisely-Carbon-Pricing-Revenue-Recycling-Report-April-2016.pdf.

CBI (2020), *Sustainable debt: Global state of the market 2020*, Climate Bonds Initiative, London, www.climatebonds.net/resources/reports/sustainable-debt-global-state-market-2020.

CBI (2019), *Green bonds: The state of the market 2018*, Climate Bonds Initiative, London, www.climatebonds.net/resources/reports/green-bonds-state-market-2018.

Ceres (2020), "New York State Common Retirement Fund becomes first US pension fund to commit to net-zero by 2040", 9 December, Ceres, Boston, www.ceres.org/news-center/press-releases/new-york-state-common-retirement-fund-becomes-first-us-pension-fund.

CFLI (2019), *Financing the low-carbon future: A private-sector view on mobilizing climate finance*, Climate Finance Leadership Initiative, www.assets.bbhub.io/company/sites/55/2019/09/Financing-the-Low-Carbon-Future_CFLI-Full-Report_September-2019.pdf.

Climatescope (2016), *Nepal Renewable Energy Subsidy Policy*, 2073 BS, Climatescope, https://aepc.gov.np/uploads/docs/2018-06-19_RE%20Subsidy%20Policy,%202073%20(English).pdf

CPR (2021), "Managing a fair transition away from coal in India", *Centre for Policy Research*, New Delhi, www.cprindia.org/managing-fair-transition-away-coal-india.

Deutsche Umwelthilfe (2021), *Strengthening circularity in photovoltaics: Challenges and opportunities along the lifecycle*, www.duh.de/fileadmin/user_upload/download/Pressemitteilungen/Kreislaufwirtschaft/210310_White_Paper_Strengthening_Circularity_in_Photovoltaics_ENG_FINAL.pdf.

DNV GL (2020), "Energy transition outlook 2020: A global and regional forecast to 2050", https://eto.dnv.com/2020#ETO2019-top (accessed 26 June 2021).

Dunbar, M. (2013), *Engaging the Private Sector in Skills Development*, Health & Education Advice and Resource Team (HEART), Oxford Policy Management, Oxford, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/213937/engaging-private-sector-skills-development.pdf.

EAFO (2021), "Norway", European Alternative Fuels Observatory, www.eafo.eu/countries/norway/1747/incentives.

ECIU (2021), "Net zero tracker", *Energy & Climate Intelligence Unit*, https://eciu.net/netzerotracker (accessed 26 June 2021).

ECREEE (2015), *ECOWAS Renewable Energy Policy*, ECOWAS (Economic Community of West African States) Centre for Renewable Energy and Energy Efficiency, Praia, www.ecreee.org/sites/default/files/documents/ecowas_renewable_energy_policy.pdf.

EECA (2021), "Funding for heaters and insulation", Energy Efficiency & Conservation Authority, www.eeca.govt.nz/our-work/programmes-and-funding/efficient-homes/funding-for-heaters-and-insulation/.

EIB (2017), *CAB Newsletter 10th anniversary*, European Investment Bank, Luxembourg, www.eib.org/en/investor_relations/documents/eib-cab-10-years-newsletter.htm# (accessed 26 June 2021).

Energy Poverty Observatory (2020), "Inability to keep home adequately warm", www.energypoverty.eu/indicator?primaryId=1461.

Environmental Finance (2020), "Environmental finance bond database", www.bonddata.org/ (subscription required).

EurObserv'ER (2020), "Policy and statistic reports: France", www.eurobserv-er.org/eurobserver-policy-files-for-all-eu-28-member-states/.

European Commission (2021a), "EU taxonomy for sustainable activities", European Commission, www.ec.europa.eu/info/business-economy-euro/banking-and-finance/sustainable-finance/eu-taxonomy-sustainable-activities_en.

European Commission (2021b), "Renovation wave", https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/renovation-wave_en.

European Commission (2020a), "A renovation wave for Europe – Greening our buildings, creating jobs, improving lives", EUR-Lex, COM(2020) 662 final, https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1603122220757&uri=CELEX:52020DC0662.

European Commission (2020b), "State aid: Commission approves competitive tender mechanism to compensate for early closure of hard coal-fired power plants in Germany", https://ec.europa.eu/commission/presscorner/detail/en/IP_20_2208.

European Commission (2018), *Impacts of circular economy policies on the labour market – Final report and Annexes*, Cambridge Econometrics, Directorate-General for Environment, ICF and Trinomics, https://op.europa.eu/en/publication-detail/-/publication/fc373862-704d-11e8-9483-01aa75ed71a1/language-en.

Equinor (2020), Energy perspectives 2020: Long-term macro and market outlook, www.equinor.com/en/sustainability/energy-perspectives/EP-2020.html.

Faaij (2018), *Securing sustainable resource availability of biomass for energy applications in Europe; review of recent literature*, University of Groningen, Groningen.

FBI (2020), *Virtual Power Plant Market Size*, Fortune Business Insights, Pune.

Frankfurt School–UNEP Centre and BNEF (2020), *Global trends in renewable energy investment 2020*, Frankfurt School-United Nations Environment Programme Centre and Bloomberg New Energy Finance BNEF.

Gesley, J. (2020), "Germany: Law on phasing-out coal-powered energy by 2038 enters into force", www.loc.gov/law/foreign-news/article/germany-law-on-phasing-out-coal-powered-energy-by-2038-enters-into-force/.

Greenpeace (2015), *Energy [r]evolution: A Sustainable World Energy Outlook 2015*, Greenpeace international. www.duesseldorf.greenpeace.de/sites/www.duesseldorf.greenpeace.de/files/greenpeace_energy-revolution_erneuerbare_2050_20150921.pdf.

Government of the Netherlands (2021), "Government stimulates geothermal heat", www.government.nl/topics/renewable-energy/government-stimulates-geothermal-heat.

Government of United Kingdom (2019), "Green Finance Strategy: Transforming Finance for a Greener Future", Crown Publishing, London, www.assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/820284/190716_BEIS_Green_Finance_Strategy_Accessible_Final.pdf.

HYBRIT (2021), "Research project 1", Hybrit, LKAB-SSAB-Vattenfall, www.hybritdevelopment.se/en/research-project-1/.

ICEF (2018), "Direct Air Capture of Carbon Dioxide – ICEF Roadmap 2018", ICEF – Innovation for Cool Earth Forum, Tokyo, December, www.icef-forum.org/pdf/2018/roadmap/ICEF2018_DAC_Roadmap_20181210.pdf.

IEA (2021a), "Global energy review: CO_2 emissions in 2020: Understanding the impacts of Covid-19 on global CO_2 emissions", International Energy Agency, Paris, www.iea.org/articles/global-energy-review-co2-emissions-in-2020.

IEA, (2021b), "Net Zero by 2050: A Roadmap for the Global Energy Sector", IEA, Paris.

IEA (2020a), *World Energy Investment 2020*, IEA, Paris.

IEA (2020b), *Global Energy Review 2020*, IEA, Paris.

IEA (2020c), "Energy Technology Perspectives 2020 - Special Report on Carbon Capture, Utilisation and Storage", IEA, Paris, September, https://iea.blob.core.windows.net/assets/181b48b4-323f-454d-96fb-0bb1889d96a9/CCUS_in_clean_energy_transitions.pdf.

IEA (2018), Renewable Heat Policies, IEA, Paris.

IEA, IRENA, UN, WBG and WHO (2021), *Tracking SDG7: The Energy Progress Report 2021*, IEA, International Renewable Energy Agency, United Nations, World Bank Group, World Health Organisation, World Bank, Washington, D.C.

IEEFA (2020a), "Dutch asset manager Robeco to divest thermal coal, oil sands holdings by year's end", 25 September, Institute for Energy Economics and Financial Analysis, www.ieefa.org/dutch-asset-manager-robeco-to-divest-thermal-coal-oil-sands-holdings-by-years-end/.

IEEFA (2020b), "U.K.'s biggest pension fund to divest from fossil fuels", 29 July, IEEFA, www.ieefa.org/u-k-s-biggest-pension-fund-to-divest-from-fossil-fuels/#:~:text=The%20Guardian%3A,landmark%20move%20for%20the%20industry.

ILO (n.d.-a), "Decent work", International Labour Organization, Genève www.ilo.org/global/topics/decent-work/lang--en/index.htm.

ILO (n.d.-b), "Disability and work", ILO, Genève, www.ilo.org/global/topics/disability-and-work/lang--en/index.htm.

IMO (2015), *Third IMO greenhouse gas study 2014*, International Maritime Organization, London,

Inês, C. *et al.* (2020), "Regulatory challenges and opportunities for collective renewable energy prosumers in the EU", *Energy Policy*, Vol. 138, 111212, https://doi.org/10.1016/j.enpol.2019.111212.

IPCC (2018), *Global Warming of 1.5°C: An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change*, Intergovernmental Panel on Climate Change, Geneva.

IRENA (forthcoming-a), *Renewable Energy Targets: A Guide to Design*, International Renewable Energy Agency, Abu Dhabi.

IRENA (forthcoming-b), *Sustainable Bioenergy: A Guide to Policy Making*, IRENA, Abu Dhabi.

IRENA (forthcoming-c), *Renewable Energy Benefits: Leveraging Local Capacity for Solar Water Heaters*, IRENA, Abu Dhabi.

IRENA (forthcoming-d), *RE-organising power systems for the transition: The dual procurement of electricity for liberalized and public systems*, IRENA, Abu Dhabi.

IRENA (2021a), *Renewable Capacity Statistics 2021*, IRENA, Abu Dhabi.

IRENA (2021b), *Renewable Power Generation Costs in 2020*, IRENA, Abu Dhabi.

IRENA (2021c), "Renewable energy finance flows," (database), www.irena.org/Statistics/View-Data-by-Topic/Finance-and-Investment/Renewable-Energy-Finance-Flows, (accessed 25 May 2021).

IRENA (2021d), "Leaders summit: The energy transition priorities needed for a 1.5°C future", IRENA, Abu Dhabi, 25 April, www.irena.org/newsroom/expertinsights/2021/April/Leaders-Summit-The-Energy-Transition-Priorities-Needed-for-a-1-5C-Future.

IRENA (2021e), *Renewable energy policies for cities: Transport,* IRENA, Abu Dhabi.

IRENA (2021f), *Renewable Energy Policies for Cities: Experiences in China, Uganda and Costa Rica*, IRENA, Abu Dhabi.

IRENA (2021g), *Renewable energy policies for cities: Power sector*, IRENA, Abu Dhabi.

IRENA (2021h), *Renewable energy policies for cities: Buildings*, IRENA, Abu Dhabi.

IRENA (2021i), *Green Hydrogen Supply: A Guide to Policy Making*, IRENA, Abu Dhabi.

IRENA (2020a), *Renewable Energy and Jobs – Annual Review 2020*, IRENA , Abu Dhabi.

IRENA (2020b), *The Post-COVID Recovery: An Agenda for Resilience, Development and Equality*, IRENA, Abu Dhabi.

IRENA (2020c), *Renewable Energy Policies in a Time of Transition: Heating and Cooling*, IRENA, Abu Dhabi,

IRENA (2020d), *Power System Organisational Structures for the Renewable Energy Era*, IRENA, Abu Dhabi.

IRENA (2020e), *Electricity Storage Valuation Framework: Assessing system value and ensuring project viability*, IRENA, Abu Dhabi.

IRENA (2020f), *Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal*, IRENA, Abu Dhabi.

IRENA (2020g), *Mobilising institutional capital for renewable energy*, IRENA, Abu Dhabi.

IRENA (2020h), *Renewable energy finance: Sovereign guarantees*, IRENA, Abu Dhabi

IRENA (2020i), *Renewable energy statistics 2020*, IRENA, Abu Dhabi

IRENA (2020j), *Renewable energy finance: Green bonds*, IRENA, Abu Dhabi

IRENA (2020k), *Business Models: Innovation Landscape Briefs*, IRENA, Abu Dhabi.

IRENA (2020l), *Green Hydrogen: A Guide to Policy Making*, IRENA, Abu Dhabi.

IRENA (2020m), *Wind Energy: A Gender Perspective*, IRENA, Abu Dhabi.

IRENA (2020n), *Measuring the Socio-Economics of Transition: Focus on Jobs*, IRENA, Abu Dhabi.

IRENA (2020o), *Global Renewables Outlook: Energy transformation 2050*, IRENA, Abu Dhabi.

IRENA (2019a), *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables*, IRENA, Abu Dhabi.

IRENA (2019b), *A new world: The geopolitics of the energy transformation*, IRENA, Abu Dhabi.

IRENA (2019c), *Renewable energy auctions: Status and trends beyond price*, IRENA, Abu Dhabi.

IRENA (2019d), *Global energy transformation: A roadmap to 2050*, IRENA, Abu Dhabi.

IRENA (2019e), *Renewable Energy Market Analysis: Southeast Europe*, IRENA, Abu Dhabi.

IRENA (2019f), *Off-grid renewable energy solutions to expand electricity access: An opportunity not to be missed*, IRENA, Abu Dhabi.

IRENA (2019g), *Innovation Outlook: Smart Charging for Electric Vehicles*, IRENA, Abu Dhabi.

IRENA (2019h), *Transforming the Energy System – and Holding the Line on Rising Global Temperatures*, IRENA, Abu Dhabi.

IRENA (2019i), *Renewable Energy: A Gender Perspective*, IRENA, Abu Dhabi.

IRENA (2018a), *Renewable Energy Benefits: Leveraging Local Capacity for Offshore Wind*, IRENA, Abu Dhabi.

IRENA (2018b), *Southeast Asia case studies: Biogas programme in Viet Nam*, IRENA, Abu Dhabi.

IRENA (2018c), *Policies and Regulations for Renewable Energy Mini-Grids,* IRENA, Abu Dhabi.

IRENA (2018d), *Renewable Energy Benefits: Leveraging Local Capacity for Onshore Wind*, IRENA, Abu Dhabi.

IRENA (2017a), *Synergies between renewable energy and energy efficiency*, IRENA, Abu Dhabi,

IRENA (2017b), *Stranded assets and renewables: how the energy transition affects the value of energy reserves, buildings and capital stock*, IRENA, Abu Dhabi.

IRENA (2017c), *Adapting Market Design to High Shares of Variable Renewable Energy*, IRENA, Abu Dhabi.

IRENA (2017d), *Renewable Energy in District Heating and Cooling: A Sector Roadmap for REmap*, IRENA, Abu Dhabi.

IRENA (2017e), *Renewable Energy Benefits: Leveraging Local Capacity for Solar PV*, IRENA, Abu Dhabi.

IRENA (2017f), *Renewable Energy Benefits: Leveraging Local Capacity for Onshore Wind*, IRENA, Abu Dhabi.

IRENA (2016a), *Unlocking Renewable Energy Investment: The role of risk mitigation and structured finance*, IRENA, Abu Dhabi.

IRENA (2016b), *Renewable Energy Benefits: Measuring the Economics*, IRENA, Abu Dhabi.

IRENA (2014), *Global bioenergy supply and demand projections: A working paper for REmap 2030*, working paper, IRENA, Abu Dhabi.

IRENA Coalition for Action (2020a), *Companies in transition towards 100% renewable energy: Focus on heating and cooling*, white paper, IRENA, Abu Dhabi.

IRENA Coalition for Action (2020b), *Stimulating investment in community energy: Broadening the ownership of renewables*, white paper, IRENA, Abu Dhabi.

IRENA Coalition for Action (2018), *Community Energy: Broadening the Ownership of Renewables*, IRENA, Abu Dhabi.

IRENA and CPI (2020), *Global Landscape of Renewable Energy Finance 2020*, IRENA, Climate Policy Initiative, Abu Dhabi and London.

IRENA and CPI (2018), *Global Landscape of Renewable Energy Finance 2018*, IRENA, CPI, Abu Dhabi and London.

IRENA and IEA-PVPS (2016), *End-of-Life Management: Solar Photovoltaic Panels*, IRENA, International Energy Agency - Photovoltaic Power Systems, Abu Dhabi and Paris.

IRENA, IEA and REN21 (2020), *Renewable Energy Policies in a Time of Transition: Heating and Cooling*, IRENA, OECD/IEA and Renewable Energy Policy Network for the 21st Century, Abu Dhabi and Paris.

IRENA, IEA and REN21 (2018), *Renewable Energy Policies in a Time of Transition*, IRENA, OECD/IEA and REN21, Abu Dhabi and Paris.

Jolly, J. (2021), "Major UK pension funds worth nearly GBP 900 bn commit to net zero?", 10 March, The Guardian, www.theguardian.com/business/2021/mar/10/major-uk-pension-funds-worth-nearly-900bn-commit-to-net-zero.

Lederman, J. and D. Chow. (2021), "Biden commits to cutting U.S. emissions in half by 2030 as part of Paris climate pact", NBC news, 22 April, www.nbcnews.com/politics/white-house/biden-will-commit-halving-u-s-emissions-2030-part-paris-n1264892.

Li S. and Yu R. (2021), "China reveals co-operation with EU on green investment standards", 7 April, Financial Times, www.ft.com/content/cddd464f-9a37-41a0-8f35-62d98fa0cca0.

Louie, E. and Pearce, J. (2016), "Retraining investment for U.S. transition from coal to solar photovoltaic employment", *Energy Economics*, Volume 57, Pages 295-302, ISSN 0140-9883, https://doi.org/10.1016/j.eneco.2016.05.016.

Mao, X. D. Rutherford, L. Osipova, and B. Comer (2020), "Refueling assessment of a zero-emission container corridor between China and the United States: Could hydrogen replace fossil fuels?", *International Council for Clean Transportation,* Working Paper 2020-05, https://theicct.org/sites/default/files/publications/Zero-emission-container-corridor-hydrogen-3.5.2020.pdf.

Marston J. (2018), "Why these companies turn to coal country for skilled workers", www.edf.org/blog/2018/05/08/why-these-companies-turn-coal-country-skilled-workers.

Mazzacurati, E. (2017), "Art. 173: France's Groundbreaking Climate Risk Reporting Law", 16 January, Four Twenty Seven, www.427mt.com/2017/01/16/impact-french-law-article-173/ (accessed 26 June 2021).

McLaughlin, C. (2019), "Denmark ends district heating heat pump grants", Ammonia21, 10 January, www.ammonia21.com/articles/8776/denmark_ends_district_heating_heat_pump_grants#:~:text=Denmark%20has%20ended%20its%20support,for%20district%20heating%20heat%20pumps.

MNRE (2021), "Production linked incentive scheme 'National Programme on High Efficiency Solar PV Modules'", F. No. 283/62/2020-grid solar, Ministry of New & Renewable Energy, Government of India, https://mnre.gov.in/img/documents/uploads/file_f-1619672166750.pdf.

Müller, F., S. Claar, M. Neumann and C. Elsner (2020), "Is green a Pan-African colour? Mapping African renewable energy policies and transitions in 34 countries", *Energy Research & Social Science*, Vol. 68, 101551, https://doi.org/10.1016/j.erss.2020.101551.

OECD (2016), *Effective Carbon Rates: Pricing CO_2 through Taxes and Emissions Trading Systems*, Organisation for Economic Co-operation and Development, Paris, www.oecd.org/tax/effective-carbon-rates-9789264260115-en.htm.

OECD and Milken Institute (2018), *Guaranteeing the Goals: Adapting public sector guarantees to unlock blended financing for the U.N. Sustainable Development Goals*, OECD and Milken Institute, www.milkeninstitute.org/sites/default/files/reports-pdf/Guaranteeing-the-Goals-FINAL-4_2.pdf.

OTPP (2021), "Ontario Teachers' Pension Plan commits to net zero emissions by 2050", 21 January, Ontario Teachers' Pension Plan, www.otpp.com/news/article/a/ontario-teachers-pension-plan-commits-to-net-zero-emissions-by-2050, (accessed 26 June 2021).

Ombello, C. (2020), "1.35 cents/KWh: Record Abu Dhabi solar bid is a sober reminder to upbeat fossil fuel pundits", Clean Technica, 8 June, https://cleantechnica.com/2020/06/08/1-35-cents-kwh-record-abu-dhabi-solar-bid-is-a-sober-reminder-to-upbeat-fossil-fuel-pundits/.

Perez, C. (2002), *Technology revolutions and financial capital: The Dynamics of Bubbles and Golden Ages*, Edward Elgar Publishing, ISBN: 978 1 84064 922 2.

Petrova, V. (2021), "Germany's 2nd coal phase-out tender ends with 1,514 MW of successful bids", 5 April, https://renewablesnow.com/news/germanys-2nd-coal-phase-out-tender-ends-with-1514-mw-of-successful-bids-736871/.

REN21 (2020), *Renewables 2020 Global Status Report*, Renewable Energy Policy Network for the 21st Century Secretariat, Paris.

REN21 (2019), *Renewables in Cities 2019 Global Status Report*, REN21 Secretariat, Paris.

REN21 (2018), *Renewables 2018 Global Status Report*, REN21 Secretariat, Paris.

REN21 (2017), *Renewables 2017 Global Status Report*, REN21 Secretariat, Paris.

Renew Economy (2019), "Renewables deliver 47% of total generation in Germany so far in 2019", Renew Economy, 4 October, https://reneweconomy.com.au/renewables-deliver-47-of-total-generation-in-germany-so-far-in-2019/.

Reuters (2021), "New Zealand introduces climate change law for financial firms in world first", 13 April, Reuters, www.reuters.com/business/sustainable-business/new-zealand-introduces-climate-change-law-financial-firms-world-first-2021-04-12/.

Reuters (2020), "Germany to extend electric car subsidies to 2025", www.reuters.com/article/uk-germany-autos-subsidy-idUKKBN27W2FT.

Ripke, J. (2017), "Innovative uses of Hydrogen in Steelmaking", U.S. Department of Energy, www.energy.gov/sites/prod/files/2017/05/f34/fcto_may_2017_h2_scale_wkshp_ripke.pdf.

S&P Dow Jones Indices LLC (2021), "S&P 500", www.spglobal.com/spdji/en/indices/equity/sp-500/#overview (accessed 25 May 2021).

Sendea (2021), *Sendea Uganda: Solar Entrepreneuers Network for Decentralized Energy Access*, www.sendea.org/.

Congressional Research Service (2019), *The value of tax incentives for different types of energy resources*, CRS Reports R44852, www.fas.org/sgp/crs/misc/R44852.pdf.

Shell (2021), "The Energy Transformation Scenarios", www.shell.com/energy-and-innovation/the-energy-future/scenarios/the-energy-transformation-scenarios.html.

Shenzhen DRC (2021), *Plan for Promoting New Energy Vehicles in Shenzhen City 2021–2025* (深圳市新能源汽车推广应用方案 2021–2025), Shenzhen Development and Reform Commission of Shenzhen Municipality, 31 March, http://fgw.sz.gov.cn/zwgk/zcfgjzcjd/zcfg/content/post_8667568.html.

Shumkov, I. (2020), "Germany accepts bids for 4,788 MW in first coal phase-out tender", 4 Dec. https://renewablesnow.com/news/germany-accepts-bids-for-4788-mw-in-first-coal-phase-out-tender-723394/ (accessed 27 June 2021).

SIFMA (2020), *Capital Markets Fact Book 2020*, Securities Industry and Financial Markets Association, www.sifma.org/resources/research/fact-book/.

Skills Development Scotland (2019), "Energy sector training fund helps 4272 people", Skills Development Scotland. www.skillsdevelopmentscotland.co.uk/news-events/2019/may/energy-sector-training-fund-helps-4272-people/.

SLoCAT (2020), "E-mobility trends and targets", January 2020, Partnership on Sustainable Low Carbon Transport, https://slocat.net/wp-content/uploads/2020/02/SLOCAT_2020_e-mobility-overview.pdf.

Sovacool, B.K. and M.H. Dworkin (2015), "Energy justice: conceptual insights and practical applications", *Applied Energy*, Vol. 142, pp.435–444.

TCFD (2019), *Task Force on Climate-related Financial Disclosures: 2019 Status Report*, Task Force on Climate-Related Financial Disclosures, www.fsb.org/2019/06/task-force-on-climate-related-financial-disclosures-2019-status-report.

Teske S. (ed.) (2019), *Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5°C and +2°C*, Springer International Publishing, www.springer.com/gp/book/9783030058425.

The White House (2021), "Fact sheet: President Biden's leaders summit on climate", Briefing room, 23 April, www.whitehouse.gov/briefing-room/statements-releases/2021/04/23/fact-sheet-president-bidens-leaders-summit-on-climate/.

The Motorship (2020), "MAN ES targets 2024 for delivery of first ammonia engine", 2 June, www.motorship.com/news101/alternative-fuels/man-es-targets-2024-for-delivery-of-first-ammonia-engine.

Tuck, N. (2020), "Sweden's AP1 to divest fully from fossil fuels", 16 March, European Pensions, www.europeanpensions.net/ep/Sweden-AP1-to-divest-fully-from-fossil-fuel.php.

UNIDO (2020), *Clean Energy Mini-Grid Policy Development Guide*, United Nations Industrial Development Organization, Vienna, www.unido.org/sites/default/files/files/2021-03/CEMG_Development_Guide_EN.pdf.

United States DoE (2021), "Renewable energy tax credits", United States Department of Energy, www.energy.gov/articles/renewable-energy-tax-credits.

United States DoE (n.d.), "Federal tax credits for new all-electric and plug-in hybrid vehicles", www.fueleconomy.gov/feg/taxevb.shtml.

VDE FNN (2018), "Technical Connection Rules for Extra High-Voltage (VDE-AR-N 4130)", www.vde.com/en/fnn/topics/technical-connection-rules/tcr-extra-high-voltage

World Energy Council (2020), *World Energy Trilemma Index 2020*, World Energy Council, London, https://trilemma.worldenergy.org/reports/main/2020/World%20Energy%20Trilemma%20Index%202020.pdf.

WHO (World Health Organization) (n.d.), "Policies enabling the adoption of clean household energy", www.who.int/airpollution/household/interventions/policy/en/.

Wood Mackenzie (2020), "Off-grid renewable investment" (database), https://datahub.woodmac.com/app/main#/dashboards/5d3a1511d249d18c0f001758, (subscription required).

World Bank (2019a), "GDP (current, US$)", World Bank, Washington D.C., www.data.worldbank.org/indicator/NY.GDP.MKTP.CD.

World Bank (2019b), "10 years of green bonds: Creating the blueprint for sustainability across capital markets", World Bank, Washington D.C., www.worldbank.org/en/news/immersive-story/2019/03/18/10-years-of-green-bonds-creating-the-blueprint-for-sustainability-across-capital-markets.

WRI (2021), "Ethiopia: Expanding opportunities for women in the electricity sector", World Resources Institute, www.wri.org/just-transitions/ethiopia.

ANNEXES

ANNEX A
SECTOR-SPECIFIC TRANSITION STRATEGIES

A1 Transport

A2 Industry

A3 Buildings

ANNEX B
SOCIO-ECONOMIC FOOTPRINT OF THE TRANSITION

ANNEX A

SECTOR SPECIFIC TRANSITION

The energy transition requires changes on the supply side (discussed in Chapter 2) and on the demand side (discussed here). This annex provides sector- and technology-specific details of the transition, looking ahead at the years until 2030 and 2050.

The analysis shows that a range of technologies and strategies need to be deployed. Renewables will play a dominant role in all end-use sectors such as electricity, green hydrogen or synthetic fuels produced from green hydrogen. Bioenergy and biomass feedstocks will also play an increasing role notably in industry and the transport sector.

In industry, renewable electricity and bioenergy, clean hydrogen and carbon dioxide (CO_2) management solutions such as carbon capture and storage (CCS) and bioenergy with CCS (BECCS) play an important role. Energy-intensive industries may relocate to sites with access to low-cost renewable energy. The total share of renewables in industry grows to 66% of final consumption by 2050 (including non-energy uses).

In the transport sector, direct electrification dominates cars and commercial road vehicles while ammonia from green hydrogen and renewable methanol dominate shipping. In aviation, a mix of synthetic fuels and biofuels will be needed. Whereas total electricity will account for 49% of the transport sector's final demand (90% of which is renewable) and biofuels for 24%, synthetic fuels raise renewables' share to 82% of final consumption in transport by 2050.

In the buildings sector, efficiency dominates. This encompasses a major retrofit of buildings as well as efficient space cooling devices and appliances. These must be combined with heat pumps for space and water heating. Traditional biomass cooking stoves are largely replaced with electricity, and to a lesser extent with green gas and modern biomass cooking stoves. The share of electricity in buildings grows to 73% and the total share of renewables in buildings grows to 89% of final consumption by 2050.

The shift from fossil fuels to electricity and other forms of modern renewable energy is a major efficiency driver, resulting in a significant drop in global energy use for transport and buildings while industrial final consumption increases slightly.

Investment opportunities for end-use sectors are detailed in this annex. These are dominated by building renovations and enabling infrastructure, such as for vehicle recharging. It should be noted that the substantial investment needed for renewable energy supply – including renewable power generation and electricity grids – are accounted for on the supply side. Also, electric cars and their related battery manufacturing plants, lithium mines and so on are not counted as energy transition investments. If such investments were included, they would raise the investment needs substantially. Meanwhile, investment needs for conventional internal combustion engines and related components will decline dramatically.

Table A.1 outlines key indicators for the changes needed to move the world from where it is today to where it needs to be in 2050 in the 1.5°C Scenario. The indicators show that significant acceleration is needed across a range of sectors and technologies, from deeper end-use electrification of transport and heat powered by renewables, to direct renewable use, energy efficiency and infrastructure needs. Such a substantial acceleration would be realised by increasing investment in the energy transition starting today.

TABLE A.1 Energy Sector: Indicators of progress – status in 2018 and targets for 2030 and 2050

Energy transition component	Key Indicators / Unit	Historical 2018	Where we need to be (1.5°C Scenario) 2030	2050	Implications/key actions
RENEWABLES	**Renewable energy share of TPES** (%)	14 %	38 %	74 %	Stabilise primary energy demand with improved efficiency (including circular economy practices), accelerated deployment of renewables and other clean energy technologies.
	Renewable energy share of power generation (%)	25 %	65 %	90 %	Emphasise solar and wind deployment, but also maximise solid biomass and biogas in the niche applications where they make sense.
	Renewable energy share of TFEC (%)	17 %	38 %	79 %	Besides electrification, keep strong focus on solar thermal heating in buildings and liquid biofuels in transport.
	Biomass - supply (EJ/yr)	54 (EJ/yr)	99 (EJ/yr)	153 (EJ/yr)	Bioenergy should be obtained in ways that are environmentally, socially and economically sustainable.
ENERGY EFFICIENCY	**TPES** (EJ/yr)	598 (EJ/yr)	590 (EJ/yr)	614 (EJ/yr)	Promote efficiency standards and efficient appliances and create conditions for project developers that speed the deployment of energy efficiency technologies.
	Energy intensity improvement rate[d] (%)	1.2 %	2.6 %	2.9 %	
	TFEC (EJ/yr)	378 (EJ/yr)	373 (EJ/yr)	348 (EJ/yr)	

a. Excludes electricity needs for green hydrogen.

b. Includes battery and plug-in hybrid electric cars.

c. Includes energy, process, non-energy use emissions along with CO_2 captured by CCS, CCU, BECCS and other carbon removal processes.

d. Energy efficiency intensity is measured in terms of primary energy use divided by gross domestic product (GDP). This shows the amount of energy required to generate one unit of GDP.

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

Energy transition component	Key Indicators Unit	Historical 2018	Where we need to be (1.5°C Scenario) 2030	2050	Implications/key actions
ELECTRIFICATION OF END-USES	**Electricity share in TFEC[a] (direct)** (%)	21 %	30 %	51 %	Focus on electric mobility and electrifying heat in buildings and industry, and on synthetic fuels and feedstocks.
	Electricity consumption (direct)[a] (TWh/yr)	22 315 TWh/yr	31 070 TWh/yr	49 275 TWh/yr	
	Electric cars stock[b] (million)	>6 million	381 million	1 780 million	Create the conditions for the electric mobility market to develop. Deploy and incentivise charging infrastructure. Promote sector coupling and circular economy principles.
	Heat pumps installations (million)	38 million	182 million	394 million	Promote alternative heating technologies such as heat pumps. Heat pumps achieve energy efficiencies three to five times higher than fossil-fuelled boilers and can be powered by renewable electricity.
HYDROGEN AND ITS DERIVATES	**Clean hydrogen production** (EJ/yr)	0 EJ/yr	18.5 EJ/yr	73.6 EJ/yr	Set up a stable and supportive policy framework. Promote certification of hydrogen from renewable power.
	Clean hydrogen share in TFEC (%)	0 %	3 %	12 %	Promote hydrogen-based direct reduced iron furnace for steel production and for chemical productions in industry.
CO_2 REMOVALS	**Carbon capture and storage (CCS) and carbon capture and utilisation (CCU) for process and fossil fuel emissions in industry** ($GtCO_2$ captured/yr)	0.01 $GtCO_2$ captured/yr	1.3 $GtCO_2$ captured/yr	3.4 $GtCO_2$ captured/yr	Apply CCS to abate remaining energy and process emissions in cement and steel sectors. Apply carbon capture (CCUS) in the production and waste management phases of chemicals and plastics and use the carbon for renewable hydrogen production.
	Biomass with CCS (BECCS) ($GtCO_2$ captured/yr)	0.002 $GtCO_2$ captured/yr	0.8 $GtCO_2$ captured/yr	4.5 $GtCO_2$ captured/yr	Use biomass with CCS (BECCS) to produce negative emissions that can offset the remaining emissions of the power, cement and chemicals sector in the lifecycle.
CO_2 EMISSIONS	**CO_2 emissions (net)[c]** ($GtCO_2$/yr)	36 $GtCO_2$/yr	22.9 $GtCO_2$/yr	-0.4 $GtCO_2$/yr	Renewables and energy efficiency measures, combined with deep electrification of end use applications can provide over 90% of the reductions required by 2050.

The rate of change in the 1.5°C Scenario is daunting – much of today's energy infrastructure and capital stock will need to be replaced in the next three decades to translate this vision into a reality. Ultimately, the speed and extent of movement in this direction will determine the world's progress towards the goals of the Paris Agreement. The world needs to capitalise now on the renewed commitments by countries to take immediate, collaborative and concrete actions to meet the challenge of climate change (IRENA, 2021a).

Chapter 2 summarises the technological avenues for the 1.5°C Scenario. The following discussion provides further details on the end-use sectors of transport, industry and buildings. IRENA will conduct more studies on these topics and will further engage stakeholders and countries to discuss the actions needed in each of these sectors.

Total decarbonisation of all sectors is challenging but feasible under the 1.5°C Scenario. Proven technologies for a net zero energy system already exist.

A.1 TRANSPORT

The mobility of people and goods across the globe plays a vital role in today's economy and society. The transport sector is responsible for close to a quarter of global-energy-related CO_2 emissions due to its heavy reliance on fossil fuels. With the global demand for transport services expected to increase in future years, it is crucial to sustainably transform the sector and advance towards a zero-carbon sector.

In IRENA's 1.5°C Scenario, transport would see a faster and more profound transformation with accelerated deployment of low-carbon solutions, as compared to current projections. Key shifts in this scenario include the following:

- Transport would see accelerated electrification and an associated deployment of charging infrastructure in the coming decades. The share of electricity in final energy consumption would rise from 1% in 2018 to 49% by 2050. Electric vehicles would account for more than 80% of all road transport activity by 2050. Such a transition implies that close to a third of all light-duty vehicle sales and a fifth of truck sales over the current decade to 2030 should be electric.
- Total liquid biofuel production would need to grow almost five fold by 2050, contributing 25% of the overall energy demand in the transport sector.
- Hydrogen and its derivatives would offer a solution to transport needs that are hard to meet through direct electrification, mitigating close to 2.2 gigatonnes of CO_2 ($GtCO_2$) emissions in the 1.5°C Scenario compared to the Planned Energy Scenario in 2050.
- A combination of energy efficiency measures and low-carbon approaches would reduce transport consumption from 121 exajoules (EJ) in 2018 to close to 94 EJ by 2050. Adoption of stringent efficiency standards for new cars and trucks can reduce cumulative emissions in road transport by an estimated 15 $GtCO_2$ equivalent until 2050.
- Beyond technologies, innovative mobility services and a modal shift from passenger cars to public transport (electric railways or trams), and from trucks to electric railways in the case of freight, would need to be promoted.

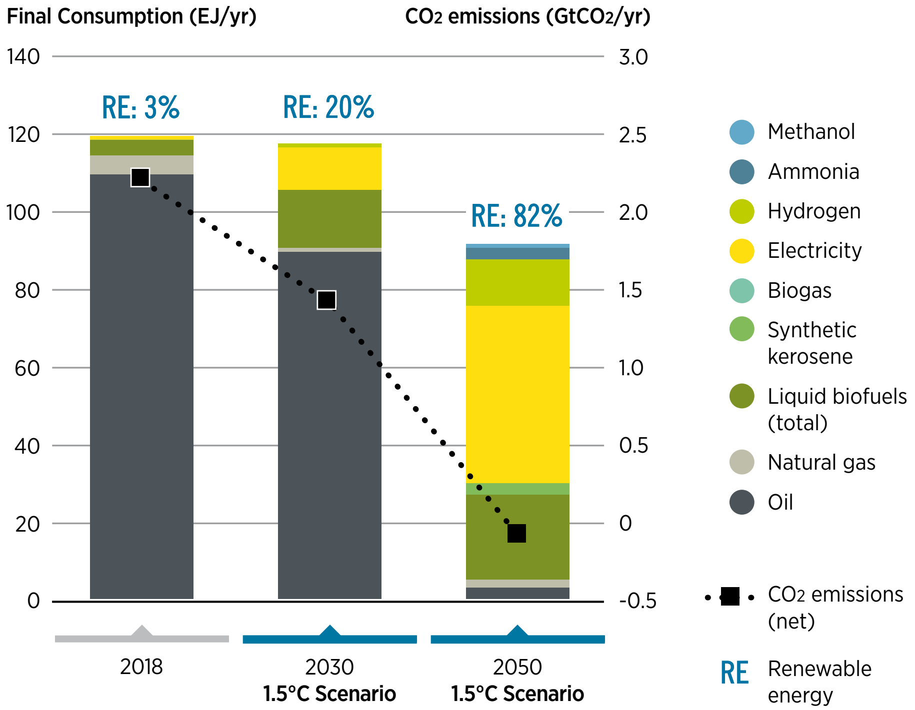
The combination of energy transition options adopted in IRENA's 1.5°C Scenario would lead to a drastic reduction in transport emissions from 8.2 $GtCO_2$ in 2018 to 0.4 $GtCO_2$ in 2050. Such a radical transition entails scaling up energy transition investments in the transport sector amounting to USD 11.3 trillion in the period to 2050. In annual terms, USD 375 billion per year on average will be needed over the next three decades for measures including deploying charging infrastructure for electric vehicles, liquid biofuels production and greater energy efficiency.

A.1.1 Overview and trends

The transport sector contributed total emissions of almost 8.2 $GtCO_2$ in 2018. The sector's energy consumption was 118 EJ (or around 2820 million tonnes of oil equivalent [Mtoe]), dominated by oil (92%) followed by small amounts of natural gas (4%), biofuels (3%) and electricity (1%). Three-quarters of the sector's energy consumption occurred in road transport alone.

The electrification of transport is showing signs of disruptive change. Global sales of electric cars in 2020 grew 43% compared to 2019, to reach 3.2 million units, accounting for 4.2% of global new car sales (Irie, 2020). Meanwhile, global biofuels production and use in the transport sector continue to rise as more countries commit to higher blending targets, such as in Brazil, India and Indonesia (REN21, 2020). Recent innovations and pilot projects also point towards the potential to increase the use of alternative fuels in the form of hydrogen, ammonia, methanol and synthetic kerosene, in particular for use in aviation and shipping (IRENA, 2021b).

FIGURE A.1 **Total energy consumption and CO_2 emissions in transport**



Under the 1.5°C Scenario, renewable electricity use could increase significantly, providing 44% of total transport energy consumption by 2050. A combination of low-carbon approaches would cut transport emissions to just 0.4 $GtCO_2$ annually by 2050, a 97% reduction compared to 2018.

TABLE A.2a Transport: Indicators of progress – status in 2018 and targets for 2030 and 2050

Energy transition component	Indicators / Unit	Historical 2018	Where we need to be (1.5°C Scenario) 2030	Where we need to be (1.5°C Scenario) 2050	Implications/Key actions
Energy transition strategy and components					
ENERGY CONSERVATION AND EFFICIENCY	**Transport – TFEC** (EJ)	121 EJ	122 EJ	93 EJ	• Improve energy efficiency through novel technologies and operational measures. • Accelerate modal shift in transport from road and aviation to rail and public transport. • Reduce travel demand.
ELECTRIFICATION IN END-USE SECTORS (DIRECT)	**Share of electricity in TFEC** (%)	1 %	9 %	49 %	• Promote the rapid electrification of road transport. • Support battery and charging research and development (R&D), considering both mobility and grid needs.
RENEWABLES (DIRECT USES)	**Biofuels share in transport TFEC** (%)	3 %	13 %	24 %	• Broaden and scale up the sustainable production and use of biofuels.
HYDROGEN AND ITS DERIVATIVES	**Clean hydrogen share in transport TFEC** (%)	<0.1 %	0.7 %	12 %	• Explore hydrogen as a potential transport fuel for road, aviation and shipping. • Introduce and scale up the use of alternative fuels though measures to support early demand.
	Ammonia, methanol, synthetic fuels share in transport TFEC (%)	<0.1 %	0.4 %	8 %	
CO_2 emissions					
CO_2 EMISSIONS	**Direct** ($GtCO_2$/yr)	8.2 $GtCO_2$/yr	6.7 $GtCO_2$/yr	0.4 $GtCO_2$/yr	Encourage strong commitments from national, regional and regulatory bodies to reach net zero emissions in transport.

Note: TFEC = total final energy consumption.

TABLE A.2b Transport: Energy transition investments

	2017-2019	2021-2050 (1.5°C Scenario)
Transport total (USD billion/ year)	69 USD billion/year	375 USD billion/year
ENERGY EFFICIENCY	65 USD billion/year	157 USD billion/year
LIQUID BIOFUELS PRODUCTION	2 USD billion/year	87 USD billion/year
CHARGING INFRASTRUCTURE FOR ELECTRIC VEHICLES	2 USD billion/year	131 USD billion/year

Note: Electric cars, the related battery manufacturing plant, lithium mines etc. are not counted as energy transition investments.

A.1.2 Transitioning towards decarbonisation

A combination of actions will be needed to achieve the massive reduction in emissions needed in the transport sector.

- **Accelerating the adoption of electric vehicles for road transport, in parallel with decarbonisation of the power supply, is the single-most important lever for the decarbonisation of the transport sector.** Technological progress – notably, the evolution of batteries – has greatly improved the economic case for electric vehicles in recent years, and the scope of application is quickly expanding to a broader set of road vehicle segments and types of services. If ongoing cost reduction trends consolidate, by 2050 the bulk of global road transport services could be delivered cost-effectively with electric technology. In IRENA's 1.5°C Scenario, electric vehicles account for more than 80% of all road transport activity by 2050 (88% of the technology mix in light-duty vehicles and 70% in heavy-duty vehicles). To meet these targets, close to a third of all light-duty vehicle sales and a fifth of truck sales over the current decade to 2030 should be electric.
- **Electrification also has a role to play in the deeper decarbonisation of the rail sector.** Electricity already plays an important role in this sector, accounting for 41% of the energy use in trains worldwide. Electric train technology is mature and has been applied for decades. Further electrification is technically possible and can be cost-effective in a broad set of circumstances.
- In addition to electrification, a decarbonisation of the transport sector in line with the goals of the Paris Agreement would require **scaling up the adoption of renewable fuels including sustainable biofuels, hydrogen and synthetic fuels.** In IRENA's 1.5°C Scenario, the production of sustainable liquid biofuels needs to be scaled up five fold compared to today's level. Biofuels, hydrogen and renewable-based synthetic fuels can be used in the remaining stock of combustion locomotives and for those routes where low-capacity factors make electric systems unattractive. Renewable power based fuels would account for around 11% of the final energy consumption of land-based transport by 2050. For the aviation sector, the use of biojet fuels would comprise 47% of the total fuel consumption, or around 204 billion litres of biofuels produced annually in the 1.5°C Scenario. The use of synthetic kerosene is also introduced in IRENA's 1.5°C Scenario, composing up to 23% of fuel use by 2050 with almost 100 billion litres of fuel required. Liquefied natural gas as a transition fuel in the international shipping sector would comprise 7% in 2030, but by 2050, investments in low-carbon fuel and ships would see ammonia, methanol and hydrogen composing almost 60% of the fuel mix.

- **The adoption of stringent efficiency standards for these new transport modes, along with behavioural changes, is crucial.** In addition to a drastic shift in the technology mix delivering energy services, structural changes in how mobility services are delivered in the first place can help facilitate decarbonisation. Substantial potential exists for a modal shift from private passenger cars to collective transport (buses and trains), as well as from passenger aviation and road-based freight to rail.
- **The introduction of novel aircraft running on hydrogen and electricity (or hybrids) by 2035 for regional short-haul flights will further increase the overall energy efficiency gains for aviation.** Electric aircraft are powered by batteries and offer the advantages of more energy-efficient motors and being fully carbon neutral if powered by 100% renewable electricity. Electric-battery-driven aircraft can be up to 1.8 times as energy efficient as conventional aircraft (Gnadt *et al.*, 2019; Schäfer *et al.*, 2019). Hydrogen aircraft technologies can either combust hydrogen in a jet engine or use it in fuel cells to produce electricity to drive propellors, with the latter approach currently favoured by developers. Both systems demand less energy and have greater emission reduction potential compared to conventional aircraft (Clean Sky 2 JU and FCH 2 JU, 2020). Airbus's recently revealed concepts for hydrogen-powered zero-emissions aircraft, which the company aims to be in service by 2035, is an encouraging sign. In IRENA's 1.5°C Scenario, electric and hydrogen aircraft together can replace 35% of short-haul flights of less than 1100 kilometres. Together, hydrogen and electricity would comprise around 14% of the aviation sector's energy consumption by 2050.

IRENA's analysis of the 1.5°C Scenario shows that a combination of efficiency measures and low-carbon approaches, as listed above based on transport mode, would reduce transport consumption to 93 EJ by 2050. In this scenario, electricity would account for 49% of consumption (90% of which is supplied by renewables), accompanied by a significant uptake of biofuels (25%) compared to today's levels (3%), as well as a mixture of clean hydrogen and its derivatives providing around 21% of the fuel mix; fossil fuels would provide the remaining consumption (around 5%). At the same time, with increased environmental awareness and the long-term impacts of the pandemic, a smaller increase in transport demand is projected compared to the Planned Energy Scenario, especially in the aviation sector.

BOX A.1 Status of battery technology

Battery storage is a key building block of the transformation towards net zero emission energy systems. Inexpensive, mass-produced batteries will enable cost-effective decarbonisation of the road transport sector – which today accounts for about a fifth of global energy-related CO_2 emissions. Furthermore, batteries can store cheap, carbon-neutral solar and wind generation, contributing to the safe, reliable operation of power systems with very high shares of renewables. Batteries can also support a wider range of services in the power sector, including frequency response, reserve capacity and black-start capability, among others (IRENA, 2017).

Battery technology has experienced impressive progress over the last decade, with costs declining around 90%. The cost of lithium-ion battery packs, typically used in electric vehicles, exceeded USD 1100/kilowatt hour (kWh) in 2010 but has fallen to USD 137/kWh in 2020 (BNEF, 2020). If current trends continue, average costs could soon break the USD 100/kWh mark, a figure often cited as the threshold for light-duty road vehicles to reach up-front cost parity with internal combustion vehicles. By 2030, battery pack prices could reach USD 61/kWh (BNEF, 2021), further improving the cost competitiveness of electric vehicles.

At the same time, the global battery production capacity is growing exponentially. Battery production capacity for electric vehicles reached 180 gigawatt hours (GWh) per year in 2020, and the pipeline for large battery factories (>1 GWh capacity) now includes 181 plants with a planned capacity of 3 terawatt hours per year by 2030 (Moores, 2021). Such capacity would enable the production of 48 million light-duty vehicles annually, more than half of the global market in recent years.*

Existing battery technology is quickly reaching commercial maturity to enable decarbonisation of some energy services, for example, road transport, short-term power storage and ancillary services. Long-duration power storage (tens to hundreds of hours), aviation and maritime shipping are candidates to benefit from improved battery technology in the future. Each of these applications requires batteries that are optimised for their specific needs (Trahey *et al.*, 2019).

For example, regional commercial flights of up to 600 nautical miles could be enabled if batteries reached an energy density of 800 Wh/kg (Schäfer *et al.*, 2019) (about three to four times higher than today's technology). Batteries for aviation need to deliver large amounts of power output to enable safe take-off and landing operations; they also need to charge rapidly to enable short turn-around times for airlines and to operate under very stringent reliability and safety standards. Further research and development is needed to expand the scope of battery use in the energy transformation and to unleash their full decarbonisation potential.

* Assuming 80% of the production is dedicated to light-duty electric vehicles, and an average battery pack size of 50 kWh.

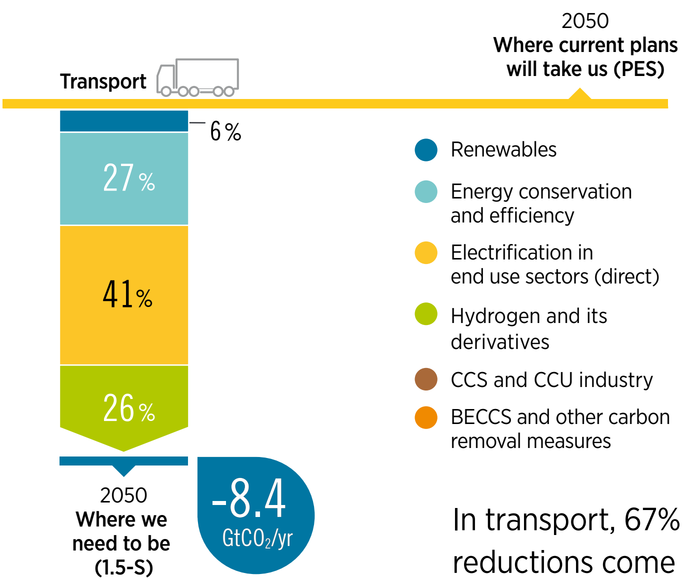
A.1.3 Opportunities for investors

To achieve the transformation envisioned in the transport sector, at least USD 11 trillion will need to be invested in the sector by 2050. The bulk of investments are needed in energy efficiency improvements for all transport modes (42% or USD 157 billion annually) and in charging infrastructure for electric vehicles (35% or USD 131 billion annually). Additional investments will be needed in supply chain expansion for electric vehicles and battery factories. The implications for mining and mineral supply chains require attention as well. Although the mining investment will be limited to those countries that have the natural resources, the need for these resources is global and growing. With the increasing use of biofuels, as well as hydrogen and its derivatives, additional investments will be needed for the expansion of production facilities, batteries, electrolysers and logistics. (For an in-depth discussion of the investment required, see Section A.2.2.)

A.1.4 Carbon dioxide emissions

As a result of a massive transition in the transport sector, as outlined in the 1.5°C Scenario, the sector's annual emissions will be reduced from 8.2 $GtCO_2$ in 2018 to 6.5 $GtCO_2$ by 2030 and 0.4 $GtCO_2$ by 2050. Electrification measures will be responsible for 41% of total CO_2 reductions in the sector, followed by energy efficiency improvements contributing 27%, hydrogen and its derivative fuels contributing 26%, and biofuels and biogas contributing the remainder.

FIGURE A.2 Emission reductions in transport in 2050



In transport, 67% of emission reductions come from direct electrification and hydrogen.

A.2 INDUSTRY

The industrial production of key materials is an essential enabler of modern economies. As countries develop, demand for such material continues to grow. However, many production processes are carbon intensive, making industry responsible for 12 $GtCO_2$ per year in 2018, around a third of human-induced CO_2 emissions (excluding land-use emissions). Of this 12 Gt, energy use accounts for 10 Gt annually and the remaining 2 Gt is process-related emissions, which can be particularly difficult to address. In general, decarbonising industry is challenging due to the complexity of the processes involved, a relative lack of economically viable technical solutions for reducing CO_2 emissions and the importance of competitive industries to national economies.

Among industrial sectors, iron and steel, cement, chemicals and petrochemicals contribute the largest share of emissions (around 70%), and the major economic blocs of China, the United States and the European Union account for a large share of overall industrial production. The initial focus of efforts to reduce emissions in industry should therefore be concentrated on these sectors and countries.

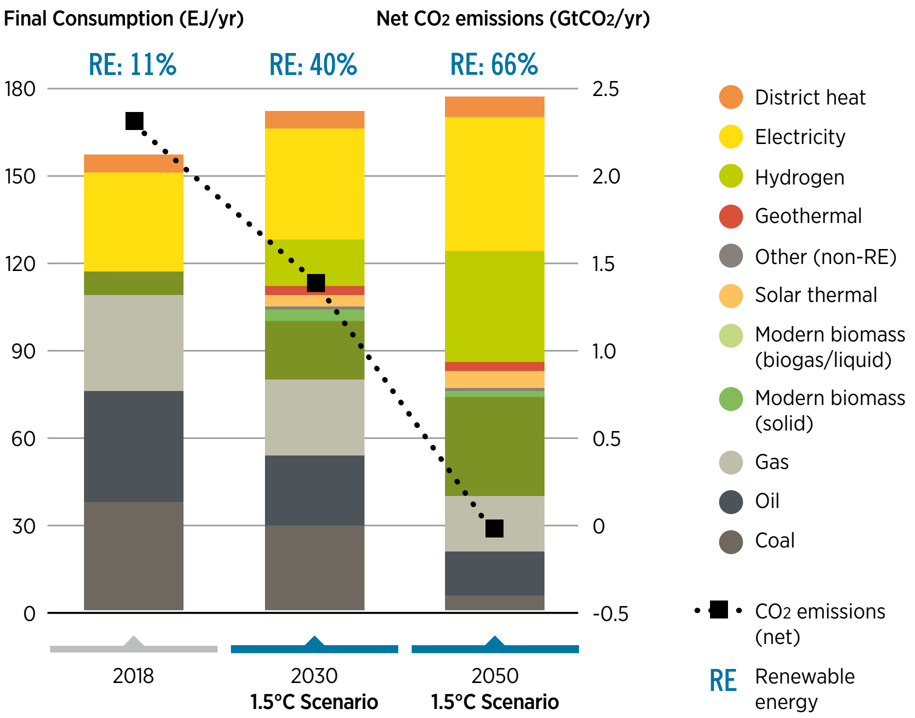
Reaching zero emissions across the industrial sectors will require radical shifts in how materials are produced, consumed and disposed.

IRENA's 1.5°C Scenario proposes a portfolio of clean energy technologies and strategies to decarbonise industry, built on five pillars:

1. **Reduced demand and improved energy and materials efficiency.** Along with circular economy practices and structural changes, this would lead to substantial reductions in industrial energy consumption by 2050.
2. **Direct use of clean electricity produced predominantly from renewable sources.** The direct electrification share in industry would rise from 28% in 2018 to 35% by 2050. For low-temperature industrial heat needs, heat pump installations would increase to 80 million by 2050.
3. **Direct use of renewable heat and biomass** – including solar thermal, geothermal, biofuels and bioenergy feedstocks. For medium- and high-temperature heat requirements, as well as for chemical feedstocks, biomass will play a significant role, requiring over 36 EJ of biomass by 2050, up from 8 EJ in 2018.
4. **Indirect use of clean electricity** via synthetic fuels and feedstocks, predominantly using renewable electricity. The use of hydrogen and synthetic fuels and feedstocks in industry would climb to over 38 EJ by 2050.
5. **Use of carbon dioxide removal and carbon capture and storage measures** – including bio-energy with carbon capture, utilisation and/or storage (BECCS). Some emissions, particularly process emissions, cannot be addressed by other means, and the combination of biomass with CCS could deliver some negative emissions. In 2050, around 4.5 $GtCO_2$ would be captured by BECCS and CCS in industry.

To achieve the complete decarbonisation of industry proposed under the 1.5°C Scenario, investment in energy transition technologies in industry would have to increase significantly, amounting to USD 14.5 trillion over the period to 2050 or on average USD 486 billion per year. As a result, the industrial sector would see significant reductions in CO_2 emissions, from 5.4 $GtCO_2$ in 2018 to -1 $GtCO_2$ in 2050 (*i.e.*, net negative). Renewables and energy efficiency contribute close to 40% of the mitigation needs between the Planned Energy Scenario and the 1.5°C Scenario. Hydrogen and electricity supplied mostly by renewable power sources would together contribute 27% of mitigation. CCS would capture one-fifth of the emissions, and the remaining mitigation effort would be provided by BECCS and other carbon removal measures.

FIGURE A.3 **Total energy consumption and CO_2 emissions in industry**



Note: The figure includes energy demand for non-energy uses, coke oven, blast furnace, chemicals fuels and feedstocks along with industry co-generation.

By 2050 the share of renewables in the industrial sector needs to grow six fold, to 66% from 11% in 2018. Electricity would make up around 26% of the sector's energy demand, followed by hydrogen providing 22% and 20% from bioenergy.

A.2.1 Overview and trends

Modern economies are highly dependent on large-scale production of key materials such as metals, minerals, chemicals and finished goods, produced by industries around the world. As countries develop and become wealthier, demand for such materials continues to grow. However, this production currently comes with high CO_2 emissions. Industry accounts for around 28% of human-induced CO_2 emissions (excluding land-use emissions), or around 12 $GtCO_2$ in 2018 (of which 2 Gt are process related and the rest energy related). Among the industry sub-sectors, the top three emitters are iron and steel (contributing 28% of industry-related emissions), cement and lime (25%) and the chemical and petrochemical industries (17%), together representing 70% of industry-related emissions (IRENA, 2020a).

The majority of energy used in industry is currently sourced from fossil fuels and is concentrated in key countries and regions. In 2018, China was responsible for more than 30% of global energy consumption in industry, followed by the United States with 11%, the European Union with 9% and India with 7%. Only around 11% of all energy consumed in industry was renewable (including electricity and district heat) in 2018. Energy use is not the only source of emissions in the industrial sector; CO_2 emissions also must be eliminated from production processes (mainly cement and iron and steel) and from the life cycle of products. Reducing emissions and eventually reaching zero will therefore require radical shifts in how materials are produced, consumed and disposed of.

To date, however, the need to drive long-term emission reductions in industry has not received the required policy attention in most countries. The United Kingdom, being a pioneer in announcing a 2050 net zero energy target, recently launched a detailed industrial decarbonisation strategy aligned with the net zero goal (Government of the United Kingdom, 2019). A few other industrial economies are exploring options. However, on a global scale, relatively less attention has been devoted to decarbonising the industry sector. A number of reasons account for this lack of action, but two in particular are key. First, only a few economically viable CO_2 emission reduction technical solutions are currently available for these industrial sectors, and until recently little consensus existed on which options are most suitable. Second, concerns about competitiveness and the risks of carbon leakage – that is, the transfer of production to other locations where emission reduction requirements are lower – is a deterrent in promoting national decarbonising efforts (IRENA, 2020a).

TABLE A.3a Industry: Indicators of progress – status in 2018 and targets for 2030 and 2050

Energy transition component	Indicators / Unit	Historical 2018	Where we need to be (1.5°C Scenario) 2030	2050	Implications/Key actions
Energy transition strategy and components					
ENERGY CONSERVATION AND EFFICIENCY	**Industry – TFEC** (EJ)	157 EJ	172 EJ	177 EJ	• Keep a strong focus on energy efficiency by making processes ever more efficient and by setting or mandating minimum standards on energy efficiency and/or on the carbon intensity of fuels, processes and products. • Promote circular economy practices (material recycling, waste management, improvements in materials efficiency and structural changes such as reuse and recycling). • Incentivise and adopt best available technologies and efficiency standards.
ELECTRIFICATION IN END-USE SECTORS (DIRECT)	**Share of electricity in TFEC** (%)	21 %	22 %	26 %	• Promote low-carbon electricity-based heating solutions such as heat pumps and electric boilers.
	Heat pumps (million units)	0 million	35 million	80 million	
RENEWABLES (DIRECT USES)	**Biomass heat (including combined heat and power (CHP) and feed-stocks** (EJ)	8.1 EJ	25 EJ	36 EJ	• Develop sustainable bioenergy supply chains to meet the growing need for bioenergy in industry to supply heat demand, especially high-temperature heat. • Refine technologies and processes for the conversion of industrial plants to biomass-based heat.
	Solar thermal consumption (GW_{th})	4 TWh/yr	890 TWh/yr	1 291 TWh/yr	• Promote awareness of the advantages of solar thermal and create incentives for project developers that can disseminate the technology, especially for low- and medium-temperature applications.
	Solar thermal – flat plate, evacuated tube (million m^2)	5 million m^2	1 272 million m^2	1 844 million m^2	

a. The dataset in the table includes energy demand for non-energy uses , coke oven, blast furnace, chemicals fuels and feedstocks along with industry co-generation.

Energy transition component	Indicators / Unit	Historical 2018	Where we need to be (1.5°C Scenario) 2030	2050	Implications/Key actions
HYDROGEN AND ITS DERIVATIVES	**Clean hydrogen consumption** (EJ)	0 EJ	16 EJ	38 EJ	• Pilot at scale, and in multiple contexts, the use of renewably produced hydrogen to replace fossil fuel-based feedstocks and process heat (e.g., in iron and steel, methanol and ammonia production). • Incentivise demand for low-carbon products.
CCS	**CCS – CO_2 captured** ($GtCO_2$/yr)	0.01 $GtCO_2$ captured/yr	1.1 $GtCO_2$ captured/yr	2.3 $GtCO_2$ captured/yr	• Pilot at scale the selective use of CCS, mainly to capture process emissions in energy-intensive industries.
BECCS AND OTHERS	**BECCS – CO_2 captured** ($GtCO_2$/yr)	0.002 $GtCO_2$ captured/yr	0.6 $GtCO_2$ captured/yr	1.14 $GtCO_2$ captured/yr	• Pilot at scale the use of BECCS in key sub-sectors such as cement and chemicals in order to offset remaining uncaptured emissions (e.g., from clinker production).
Renewables share					
RENEWABLES[a]	**Renewable energy share (including electricity and district heating)** (%)	11 %	40 %	66 %	• Maintain a strong focus on strategies to accelerate energy efficiency improvements, clean hydrogen use and direct renewables use such as biomass and solar thermal.
CO_2 emissions					
CO_2 EMISSIONS	**CO_2 emissions with carbon capture and removal**[b] ($GtCO_2$/yr)	6.1 $GtCO_2$/yr	4.7 $GtCO_2$/yr	-1 $GtCO_2$/yr	Implement an appropriate carbon pricing mechanism in line with the real costs of the externalities and eliminate any remaining subsidies or incentives for the use of carbon-intensive fuels.
ENERGY-INTENSIVE INDUSTRIES	**Iron and steel; cement; and chemical and petrochemical – share of industry gross emissions (excl. CCS/CDR)** (%)	70 %	83 %	98 %	• Develop a shared vision and strategy and co-develop practical roadmaps involving all major players. • Collaborate across borders to share knowledge and build capacity. Support research, development and deployment, and systemic innovation.

b. Emissions represent net CO_2 emissions including CO_2 removal using CCS, CCU and BECCS along with the life cycle of petrochemicals.

Note: TFEC = total final energy consumption.

TABLE A.3b Industry: Energy transition investments

	2017-2019	2021-2050 (1.5°C Scenario)
Industry total (USD billion/ year)	95 USD billion/year	486 USD billion/year
ENERGY EFFICIENCY	45 USD billion/year	354 USD billion/year
RENEWABLES (DIRECT USES)	32 USD billion/year	45 USD billion/year
HEAT PUMPS	2 USD billion/year	24 USD billion/year
CCS AND BECCS		38 USD billion/year
CIRCULAR ECONOMY		25 USD billion/year

Note: Investments in hydrogen electrolysers, chemicals feedstocks and renewable power capacity are not included in this table.

A.2.2 Transitioning towards decarbonisation

The majority of emission reductions will be achieved through a combination of six emission reduction measures, three of which rely primarily on renewable energy (IRENA, 2020a):

- **Reduced demand and improved energy and materials efficiency.** This involves reducing energy and material demand and intensity of use through a range of actions, including energy efficiency, behavioural and process changes, relocation and the application of circular economy principles. For instance, greater efficiency in materials use could reduce the demand for new materials production, even as interesting opportunities exist for product reuse and materials recycling. Efforts to deploy low-carbon technologies need to be complemented with strategies and options to improve material efficiency and create a circular economy.

  However, not all options are within the boundaries of the industry sector. An important effort will be required in the waste management sector, especially related to steel products and plastics. This is essential to increase recovery rates of materials from products that have reached their end of life, to ensure cost-effective and efficient logistics, to develop cost-effective recycling technologies and to develop the global infrastructure to circulate these materials. Structural changes will have impacts throughout the product life cycle. The material flows across sectors will be affected by emission reduction efforts elsewhere in the economy, such as the reduced availability of blast furnace slag and fly ash for cement production, which will require new material solutions to be developed (Gielen and Saygin, 2018).

- **Direct use of clean electricity, produced predominantly from renewable sources.** Directly using clean electricity (sourced mainly from renewables) to provide energy requirements can both replace existing fossil-fuel-based electricity use and replace other energy demand through "electrification". Electricity demand is expected to continue to grow in the manufacturing industry, due in part to an electrification of production processes but also to production growth in electricity-intensive industries, such as the non-ferrous metals sector. As renewables' share in power generation grows, this increases their share in industry. Locating such industries close to renewable power plants is one option that would increase the share of renewable energy in the electricity sector.

  Already many electricity-intensive industries such as aluminium smelters are linked with generation assets that offer cheap electricity from hydropower, and this is likely to increase in the coming years. Several large manufacturing companies are integrating renewable energy power generation into their existing manufacturing plants through either solar photovoltaic (PV) panels on production facilities, wind turbines on site or other sources of renewable energy. Process technology research and development should also focus on electricity-based alternatives, ensuring that the electricity sector is decarbonised. An interesting trend is direct corporate sourcing of renewable power. These and other trends are opening up possibilities for industry and transport that make zero emissions an achievable objective.

- **Direct use of renewable heat and biomass – including solar thermal, geothermal, biofuels and bioenergy feedstocks.** This involves directly utilising renewables for energy and feedstocks, including the use of solar and geothermal for some heat requirements and the use of sustainable biomass (including through the direct use of bioenergy) for heat and for the production and use of biofuels and bioenergy feedstocks. Industry's use of solar thermal heat will rise steeply and provide 5% of the sector's heat demand. Current direct renewable energy use in industry is predominantly in the form of biofuels and waste. This is mainly due to by-products and waste use, such as bagasse and rice husk in sugar production and other traditional industries; biogas from sewage and farms for food processing and black liquor in the pulp and paper sector.

  The versatility of biomass also results in competitive uses within and between the industry sector and other sectors of the economy. Realising cost-effective and sustainable biomass potential depends on a number of factors, including local feedstock cost and availability as well as biomass logistics. In addition to biomass, solar heating and geothermal could substitute fossil fuel use. Today only certain applications of renewable energy are cost-effective, such as low-temperature process heat generation with solar water heaters and steam production from low-cost biomass residues. Breweries, dairy industries and textile processing industries are typical settings where these technologies are applied.

  Important economic, technical and logistical barriers remain. Yet in the near future and with proper policy frameworks in place, renewable energy technologies can provide practical and cost-effective alternatives for process heat generation and as a renewable carbon source for the production of chemicals and plastics (Saygin, D. and Gielen, D., 2021). Meanwhile, for medium- and high-temperature processes, bioenergy would remain critical. As such, bioenergy would constitute 20% of final energy consumption in 2050.

- **Indirect use of clean electricity via synthetic fuels and feedstocks, predominantly using renewable electricity.** This involves sourcing energy and feedstocks from hydrogen or from fuels or feedstocks produced from hydrogen (synthetic fuels or feedstocks) using CO_2 captured from non-fossil-fuel sources. The hydrogen should be "clean" and preferably "green" (*i.e.*, sourced from renewables). Hydrogen would also play an important role in the sector: its use grows to over 38 EJ by 2050 (two-thirds derived from renewables) in IRENA's 1.5°C Scenario, driven by declining costs (IRENA, 2020b).
- **Carbon capture, utilisation and/or storage (CCUS/CCS).** This involves capturing most CO_2 emissions from remaining fossil-fuel-based energy production that cannot be credibly substituted with renewables or other processes and either storing the captured CO_2 permanently or utilising the CO_2 in ways in which it will not be later released. Especially for industries with high process emissions such as cement clinker production, this option could play an important role. While renewables and energy efficiency could make a significant contribution to industrial emission reductions, their joint potential is not enough to fully decarbonise the industry sector. CCS will need to be deployed for some manufacturing of iron, ammonia, cement clinker and some chemicals.
- **Biomass coupled with carbon capture and storage BECCS and other carbon removal measures.** Additional effort will be needed to offset emissions using carbon dioxide removal technologies. These include the use of biomass in combination with CCS (BECCS), and other uses of biomass such as biomass carbon use (with proper accounting for its storage in synthetic organic materials), wood materials' use for construction (with accounting for its carbon storage effects), as well as carbonation of concrete and direct air carbon capture and storage (DACCS). These technologies are not currently deployed at any significant scale; if they are to have a meaningful impact, efforts must be ramped up quickly in the coming decades.

A.2.3 Opportunities for investors

The industrial sector's technology portfolio, as outlined in IRENA's 1.5°C Scenario, requires increasing investments in the order of USD 14.6 trillion between 2021 and 2050 (or, on average, USD 486 billion per year to 2050). More than 75% of this total investment would be needed for improving energy efficiency levels and circular economy practices. Around 14% of the total investments would be needed for deploying renewables for direct use and heat pumps. The remaining 8% of the investments are attributed to coupling CCS and BECCS units.

A strategic move could be investing in energy-intensive industries in countries with good resources and large shares of renewables. For example, this could mean coupling iron ore mining and green ironmaking in places with abundant and low-cost renewable resources, such as Australia, to create new value and supply chains while also delivering emission reductions. A shift from the use of the blast furnace–basic oxygen furnace to the green hydrogen direct reduced iron–electric arc furnace could enable a wider relocation of the sector to places where relatively low-cost and abundant renewable electricity sources are available. The prospect of wider relocation could trigger the creation of markets for greener steel, provided there is adequate infrastructure in place for transporting hydrogen along with proper trade agreements and finance flows.

Decarbonising the industry sector requires concerted actions by all countries. Yet the actions of a few key countries and regions are particularly critical. Major economies such as China, the United States, India, the European Union and the United Kingdom currently account for two-thirds of global emissions and more than two-thirds of global industrial emissions. Actions and initiatives in these major economies and economic blocs will determine whether the world's industrial processes can get on a pathway consistent with 1.5°C climate targets.

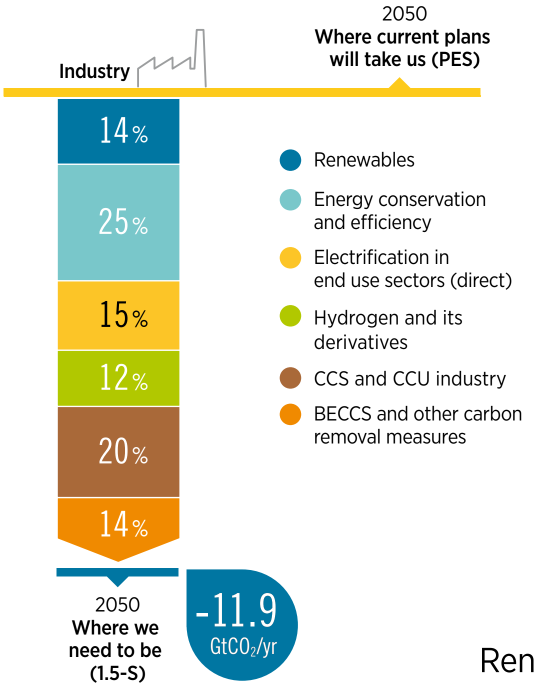
For example, in China, the world's largest producer of a range of energy-intensive commodities, the energy consumption of the industry sector accounts for 60% of gross final energy use in industry (for both energy and non-energy use), with a proportional share of emissions. However, emission reduction in the industry sector has received relatively little policy attention to date. Decarbonising China's energy-intensive industries is important not just in a national context, but also as a key enabler of the decarbonisation of the global industrial sector. Strategies for decarbonising energy-intensive industries in China include exploring the targeted use of CCS for cement kilns and outsourcing some of the energy-intensive industry activities, for example, through imports of hydrogen direct reduced iron, green ammonia or renewable methanol (Gielen, Chen and Durrant, 2021).

After China, India is the world's second-largest producer of a range of energy-intensive commodities and uses coal as a dominant fuel. Industrial activities in the country are expected to surge in the coming decades driven by rapid urbanisation, economic growth and ongoing initiatives such as "Make in India" and "Atma Nirbhar Bharat". Such advancements have significant implications for India's emission trajectory and provide a unique opportunity for the country to evolve sustainably and establish itself as a "global green manufacturing hub". Decarbonisation strategies for India's industrial sector could include: setting short- and long-term targets and goals as part of the country's updated Nationally Determined Contributions; planning and approving new greenfield projects with the best available technologies (supported by high energy efficiency standards), including clean energy fuels (renewables, clean electricity); promoting circular economy practices; deploying alternative fuels such as green hydrogen (*e.g.*, for green steel and for chemical/fertiliser production) and scaling up energy transition investments (Deore, Kukreja and Koti, 2021).

A.2.4 Carbon dioxide emissions

Industry is the second-largest emitter of energy-related CO_2, after the power sector, and is responsible for just under one-third of these emissions worldwide (when including process emissions). The 1.5°C Scenario outlines a pathway to deliver more than 100% reductions of the sector's emissions by 2050. Renewables, energy efficiency, electrification and hydrogen contribute to almost two-thirds of the mitigation needs between the Planned Energy Scenario and the 1.5°C Scenario. The remaining emission reductions would be contributed by CCS (20%) and BECCS and other CO_2 removal measures.

FIGURE A.4 Emission reductions in industry in 2050



Renewables and energy efficiency would contribute 39% of total mitigation needs in 2050, while hydrogen and electricity combined contribute 27%.

Relatively few of the technical options identified, however, are commercially mature or ready for wide adoption. Uncertainties remain about their potential and optimum use, and none will be easy to scale up. The reasons are varied and complex. They include: high costs for new technologies and processes; the need for enabling infrastructure ahead of demand; highly integrated operations and long-established practices; uneven, large and long-term investment needs; gaps in carbon accounting and business risks for first-movers, including added costs and consequent "carbon leakage" in favour of competitors. This calls for inter-linked sector-level strategies at the local, national and international levels, built on the five technology pillars of demand reduction and energy efficiency, renewable electricity, renewable heat and biofuels, green hydrogen and e-fuels, and carbon-removal technologies.

A.3 BUILDINGS

The ways that we live and work in our built environment will be transformed over the next decades under the 1.5°C Scenario. Our buildings will increasingly be smart, inter-connected, highly energy efficient and powered and heated predominantly by renewable energy. This is not only necessary to meet global climate goals, but it also presents a strong business opportunity and could be a key driver in increasing employment and the quality of our air in urban areas.

An effective transition to reach zero emissions in the buildings sector entails multiple strategies:

1 Energy efficiency should take the top priority: all new buildings should be low-energy buildings starting in 2025 and zero-energy buildings beginning in 2030; meanwhile, for existing buildings the rate of renovation will need to triple. The buildings sector is a major user of manufactured products, and the nexus with efficient construction, alternative building materials, low-emission materials and better design – combined with circular economy principles in the construction and operation of buildings – will be key in helping to achieve emission reductions in other sectors, notably in industry.

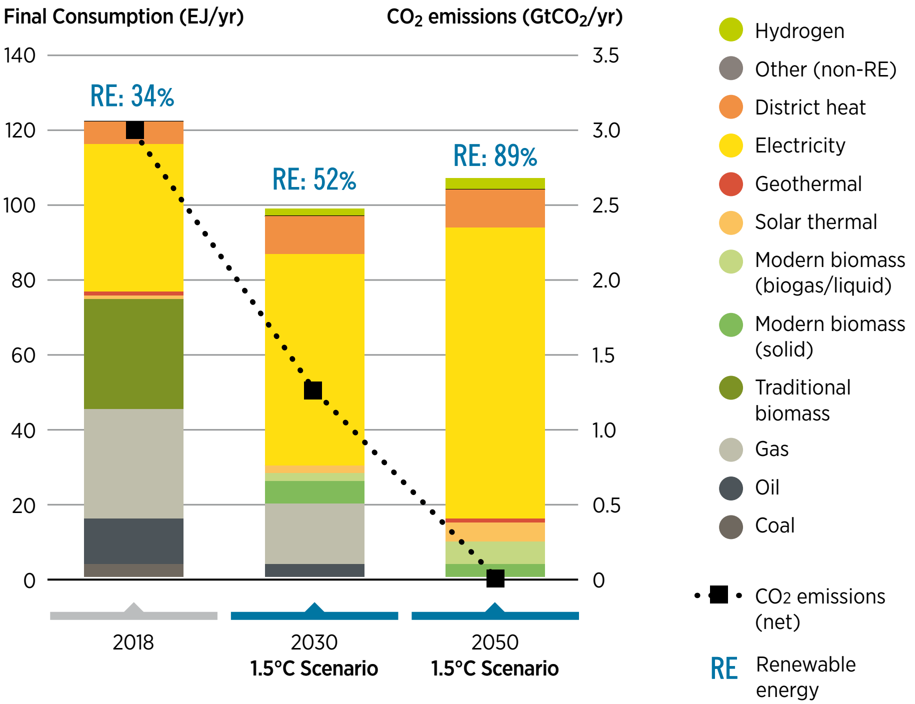
2 Electricity will be the key energy carrier, with its share of final energy use in buildings increasing from 32% in 2018 to 56% by 2030 and 73% by 2050. Such a rise implies a doubling of electricity demand in the sector by 2050 compared to the 2018 level, driven by significant electrification of heat, growth in cooling demand and electric cooking. In addition, heat pumps are a key and efficient technology and will grow eight fold by 2050.

3 There remains an important role for direct use of renewables such as biofuels and biomethane and solar thermal for heating, cooking and, along with clean hydrogen, for greening the gas system. The number of solar thermal systems will grow more than four fold from 2018. Greening the gas grid will be important for areas that have existing gas supply infrastructure; a mix of clean hydrogen and biogas represent around 8% of heating demand by 2050. Finally, traditional uses of bioenergy (representing around one-quarter of energy demand in 2018, much of it unsustainably sourced and inefficiently used) will be replaced with a combination of modern biomass cook stoves, biogas and electric stoves.

In total, this transformation will see the modern renewable energy share in the buildings sector rise from 15% in 2018 (or 40% if including traditional uses of bioenergy) to 78% in 2030 and 92% in 2050. To achieve this radical transition, USD 1.1 trillion per year will need to be invested in the sector in the period to 2050. Of this total, building retrofits, smart home and energy efficiency investments make up the bulk of the investment needs at over USD 960 billion per year. Reaching this level of investment will be challenging, since most benefits are felt only in the long term. Thus, new financing schemes and tax regimes are required to incentivise investments.

Direct CO_2 emissions in the buildings sector accounted for 9% (3 Gt) of total energy-related CO_2 emissions in 2018. The result of this energy transition in the sector is that by 2050, direct CO_2 emissions in the sector would reach zero. The key components that would mitigate almost 2.3 $GtCO_2$ when comparing the Planned Energy Scenario to the 1.5 °C Scenario are electrification (46%), energy efficiency improvements (38%), direct use of renewables (15%) and hydrogen for the remainder.

FIGURE A.5 Total final energy consumption and CO_2 emissions in buildings



By 2050 the share of renewables in buildings would ramp up to 89%, from 34% in 2018. Despite an additional 1 billion new households by 2050, overall energy consumption in buildings in 2050 would decline 14% compared to 2018.

A.3.1 Overview and trends

The buildings sector includes residential, commercial and public buildings. In 2018, buildings consumed 122 EJ (around one-third of total final energy consumption), with 30% for heating, 24% for cooking, 20% for water heating, 18% for lighting and other appliances and 8% for cooling. An important caveat of the building sector's energy demand is that in some parts of the world (*e.g.*, Africa) the sector is dominated by traditional uses of bioenergy, largely for cooking. This form of consumption makes up around one-quarter of energy demand in the sector globally. Direct use of fuels for heating is currently the largest consumer of energy in the sector, with more than two-thirds coming from fossil fuels, mainly natural gas.

Direct CO_2 emissions in the buildings sector account for 9% (3 Gt) of total energy-related CO_2 emissions. However, when including the emissions associated with electricity supply to the sector, the share of energy-related emissions applicable to building energy consumption rises to around 30%. Renewables make up a large share of energy demand in buildings, at around 40% in 2018. However, the largest component of that renewable energy consumption is met by traditional uses of bioenergy for cooking and heat. When traditional uses are excluded, the modern renewable energy share in buildings is much lower, around 15%. Modern forms of biomass still represent an important energy source in some countries, providing around 15% of heating demand (around 4 EJ). Overall, the sector has the largest share of electricity consumption at around one-third, with bioenergy (both traditional and modern) and natural gas each supplying around one-quarter of energy supply, and the remainder roughly half oil and half other sources.

Driven by population growth and rising gross domestic product, the total floor area in the sector is expected to increase 80% over the next 30 years. This is the equivalent of adding the entire residential building floor area of Germany every year (around 4 billion square metres [m^2]) for the next 30 years. Most of this growth will occur in developing and emerging economies. The sector is becoming more efficient with energy demand growing slower relative to new floor area added, compared to the past. This lower relative growth of energy demand is the result of a few key drivers: reduced traditional uses of bioenergy (which results in significant energy efficiency increases, and therefore energy savings); higher levels of building and appliance efficiency; a shift to electricity for energy services (which is more efficient) and greater adoption of other renewable sources.

TABLE A.4a Buildings: Indicators of progress – status in 2018 and targets for 2030 and 2050

Energy transition component	Indicators / Unit	Historical 2018	Where we need to be (1.5°C Scenario) 2030	Where we need to be (1.5°C Scenario) 2050	Implications/Key actions
Energy transition strategy and components					
ENERGY CONSERVATION AND EFFICIENCY	**Buildings – TFEC** (EJ)	122 EJ	99 EJ	105 EJ	• Establish and improve energy efficiency building codes and standards, including appliances (e.g., air conditioners), lighting (e.g., LED lights) and equipment (e.g., heat pumps, efficient boilers).
	Building renovation rate (% of stock per year)	1 %	2 %	3 %	• Adopt programmes for retrofitting/renovation including financing schemes, and accelerate the rate of renovations.
	Smart meters (billion units)	0.13 billion	1 billion	2 billion	• Accelerate roll-out of smart meters. • Promote energy management for load flexibility.
ELECTRIFICATION IN END-USE SECTORS (DIRECT)	**Electricity share in buildings** (%)	32 %	56 %	73 %	• Deploy high-efficiency heat pumps for space heat and for hot water heaters; use electric hot water and cooking.
	Heat pump installations (million units)	38 million	142 million	290 million	• Optimise space heating and cooling and incorporate highly efficient electric systems where possible (e.g., heat pumps).
	Heat pumps installed capacity* (GW)	760 GW	2 800 GW	5 800 GW	

Energy transition component	Indicators / Unit	Historical 2018	Where we need to be (1.5°C Scenario) 2030	2050	Implications/Key actions
RENEWABLES (DIRECT USES)	**Biomass (incl. traditional)** (EJ)	29 EJ	8.3 EJ	9.5 EJ	• Phase out traditional uses of biomass and replace them with efficient and clean cook stoves.
	Solar thermal and geothermal consumption - heating (EJ)	1.8 EJ	2.3 EJ	6.2 EJ	• Promote renewable-based heating solutions (e.g., solar thermal).
	RE based district heat generation (EJ)	0.4 EJ	4.2 EJ	7.3 EJ	• Promote renewable-based heating solutions (e.g., modern biomass and heat pumps).
RENEWABLES (POWER)	**Distributed storage (batteries)** (GJ)	3.3 GW	99 GW	2 200 GW	• Promote deployment of distributed energy resources and improve regulations for "prosumers". • Capitalise on smart homes and digitalisation to enable demand management.
HYDROGEN AND ITS DERIVATIVES	**Clean hydrogen-consumption** (EJ)	0.0 EJ	2 EJ	3.2 EJ	• Do not expand gas infrastructure, but for some existing systems prepare them for green gas.
CO_2 emissions					
CO_2 EMISSIONS	**Direct** ($GtCO_2$/yr)	2.9 $GtCO_2$/yr	1.2 $GtCO_2$/yr	0.0 $GtCO_2$/yr	• Mandate all new construction to be low-energy beginning by 2025 and zero-energy from 2030 onwards.

Note: *Estimated assuming unit capacity of 20 kW/unit.

TABLE A.4b Buildings: Energy transition investments

	2017-2019	2021-2050 (1.5°C Scenario)
Buildings total (USD billion/ year)	151 USD billion/year	1 089 USD billion/year
ENERGY EFFICIENCY	139 USD billion/year	963 USD billion/year
RENEWABLES (DIRECT USES)	7 USD billion/year	32 USD billion/year
SMART METERS		22 USD billion/year
HEAT PUMPS	2 USD billion/year	72 USD billion/year

A.3.2 Transitioning towards decarbonisation

Buildings will be central to the energy transition by offering opportunities for energy efficiency improvements, being a site for energy production through distributed energy resources, providing energy storage to the power system (both with batteries and with electric vehicles) and by allowing better grid management through electricity demand response. To realise such a transition, several different energy transition strategies need to be pursued in parallel:

- **Energy efficiency is key to enable the 1.5°C Scenario.** The energy intensity of the buildings sector, which measures the amount of energy consumed in the sector based on floor area, will decline by half by 2050. This is driven by the requirement that all new building construction will need to be low energy starting in 2025 and zero energy beginning in 2030. Meanwhile, for existing buildings the rate of renovation will need to triple, to 3% of the building stock per year – a significant increase over the historical average of just around 1% per year. Space heating energy demand decreases by about half in the 1.5°C Scenario, driven by improved efficiency and significant adoption of forms of electric heat such as heat pumps. In Europe, which has some of the world's most stringent building requirements and numerous renovation programmes, around 75% of the existing building stock is still not energy efficient. In this context, an initiative called the "renovation wave" aimed at accelerating the rate of renovation as part of the European Green Deal was introduced in 2020 (EC, 2020).

- **Electrification will continue to play a critical role in the buildings sector.** Electricity is already the single-largest energy carrier in the sector, making up 32% in 2018, and this share will rise to 73% in 2050 in the 1.5°C Scenario. This is equivalent to 21 300 terawatt hours by 2050, a doubling of electricity demand in the sector. Driving this increase is not just the wider adoption of electric appliances, but significant electrification of heat, growth in cooling demand and electric cooking.
- **In a future renewable energy system, power-to-heat will shape a significant portion of the heating sector.** Heat pumps achieve rates of energy efficiency two to five times higher than fossil-fuelled boilers and can be powered by renewable electricity. Under the 1.5°C Scenario, heat pumps will play a critical role, as their number increases from around 38 million in 2018 to around 290 million by 2050. This implies the need for 8.5 million new units to be installed every year for next three decades.
- **Electricity demand for appliances and lighting will increase 40% by 2050 in the 1.5°C Scenario.** Growth is slowed due to higher appliance efficiency and includes widespread use of smart home systems with advanced controls for lighting and better appliance management (and separately for heating and cooling). Buildings would also be an important source of load management and flexibility to the grids, with load shifting enabled by widespread use of smart home appliances and smart meters (of which more than 2 billion are installed by 2050). Meanwhile, stationary storage will increase from just 3 GW today to over 2 200 GW by 2050, often built-in combination with distributed energy supply such as solar PV.
- **Heating water with electricity needs to become even more common.** Electric water heating consumes around 3 EJ of electricity today and is a trend that is accelerating, in particular for systems that provide instantaneous, or tankless, hot water or systems that use heat pump water heaters. Electric resistance water heating can play a limited yet important role in specific applications where alternatives, notably heat pump water heaters, are not available. In the 1.5°C Scenario electricity use for water heating is accelerated, rising 3.5 times. This shift is achieved by the ease of installation when switching from a fuel-based boiler to an electric boiler.

The direct use of renewables in buildings would grow substantially.

- **Solar thermal systems would see significant growth and play an important role in some regions.** Small-scale solar systems are in wide use for domestic hot water and for heating buildings in temperate climates, and for some other limited applications requiring temperatures of less than 100°C[1] (Pauschinger, 2016). Large-scale systems are especially suited for integration with district heating networks due to economies of scale. For example, a centralised 15 megawatt solar district heating plant inaugurated in 2019 in Salaspils, Latvia, will meet about 20% of the annual heat demand from the system, with the rest being supplied by a 3 megawatt biomass boiler; a smaller-scale example consists of the 600 m^2 roof-mounted solar collectors at Wits University Junction residence in Johannesburg, South Africa (IRENA, 2020c). In 2019, around 690 million m^2 of solar thermal collector area was in place. In the 1.5°C Scenario solar thermal systems increase considerably, with collector area rising from 690 million m^2 to some 3 000 million m^2. This is large growth, but solar thermal hot water systems are mature technologies that are reliable and cost-effective in places with higher solar irradiance. Even in areas with a less-than-ideal solar resource, these systems can be built and backed up by an electric boiler.

1 Solar thermal consists of capturing solar radiation to produce heat.

- **Inefficient heating and cooking practices must be replaced with clean, efficient, modern systems.** There are two primary ways of using modern biomass in the buildings sector: for space heating and for cooking. Buildings can be heated using modern biomass through town-scale district heating systems or building-scale furnaces, both of which use feedstocks such as wood chips and pellets very efficiently. Traditionally, biomass has been used for heating and cooking in open fireplaces or stoves, and today modern biomass is being used in efficient boilers and furnaces and improved cook stoves. However, more than 2 billion people still rely on inefficient traditional use of biomass, such as fuelwood and charcoal, for cooking. Inefficient traditional cook stoves paired with solid fuels and kerosene emit indoor smoke that imperils the health of mainly women and children and causes nearly 4 million premature deaths every year. The largest share of biomass consumption in the buildings sector in 2017 was in Sub-Saharan Africa at 91% (entirely in the form of traditional uses).

  These detrimental cooking practices must be replaced with clean, efficient, modern systems that use improved cook stoves fuelled with sustainably produced bioenergy such as wood, biogas or ethanol (IRENA, 2020d). Traditional uses of biomass in cooking must be phased out in the next decade and be replaced with modern fuels and improved and modern cook stoves. Cooking is significantly transformed in the 1.5°C Energy Scenario, due in part to the complete phase-out of traditional uses of bioenergy. Demand is further reduced to 10 EJ by 2050, a result of this modern fuel switch but also significant and widespread electrification of cooking. Around 85% of cooking needs are met through electricity; the remainder is largely supplied via biomethane. The transformation will need to go hand in hand with enabling stable electricity access for the entire population.

- **Greening the gas grid will be necessary, and hydrogen and biomethane will play the predominant role.** The use of natural gas use for water and space heating in the buildings sector would decline to zero by 2050 due to widescale shift electrification, energy-saving renovations in old buildings and more energy-efficient new buildings, as well as hydrogen and biomethane taking over natural gas's role. For the latter, it is foreseen that this will be achieved by gradually increasing the levels of hydrogen and biomethane blended with natural gas and using the existing gas grid to deliver the green gases. Gas systems still remain and represent around 8% of sector energy and can be utilised if their gas is "greened".

  For this, a combination of 70% biomethane and 30% zero-carbon hydrogen is deployed. Demand for district heat also rises 60%, as people become more urbanised. In Germany, the gas grid is undergoing a 10-year, EUR 7 billion (USD 7.8 billion) renovation to switch 30% of its customers from natural gas with lower methane content (L-gas) to gas with higher methane and higher calorific content (H-gas). This is due to the decline in supplies of L-gas. Although this seems like a minor shift compared to adding hydrogen into natural gas, it comes at a significant cost (IRENA, 2019).

Overall, the 1.5°C Scenario sees a significant change in the buildings sector. Energy demand will decline around 14% to 105 EJ despite the growth in overall floor area. Several factors are attributed to this drop in demand: a large one is the phase-out of traditional uses of bioenergy, followed by significantly greater energy efficiency improvements reducing building sector energy intensity 50% from 2018 levels, and also electrification measures. The mix for energy services will also change, with 26% consumed for heating, 10% for cooking, 27% for lighting and other appliances, 21% for cooling and 17% for water heating – the largest increases are found in energy demand for cooling and appliances/lighting.

Space cooling demand increases the most of any energy service in buildings, with demand tripling. Due to increases in building envelope and cooling system efficiency, energy demand for cooling will still more than double by 2050, from 9 EJ to around 21 EJ by 2050. Overall, around 2.4 billion air conditioner units will be in operation by 2050, an increase from 0.9 billion today. District cooling grows to around 1 EJ by 2050, providing around 5% of cooling demand. Demand for district heat also rises 60%, as people become more urbanised. To supply this heat from carbon-free sources, several routes will need to be taken, from large electric boilers and electric heat pumps to municipal solid waste and bioenergy.

Coupling heating systems with thermal and seasonal storage offers important flexibility in demand in regions where winters are particularly harsh. For example, the Drake Landing Solar Community in Canada is using a long-term thermal energy storage system to store heat from solar collectors during summer to be used for space heating during winter. In coupling the power and thermal sector, Siemens-Gamesa is testing a thermal energy storage system that uses wind power to produce heat, which is stored in over 1000 tonnes of rock. This system provides a thermal storage capacity of 130 megawatt hours of electric energy at rated charging temperatures of 750°C. IRENA estimates that around 234 gigawatt hours of thermal energy storage[2] is present across the globe, a crucial enabler of reliable, secure and flexible energy systems (IRENA, 2020c).

In the 1.5°C Scenario widespread innovation will be necessary. New technologies, materials, design and business models for net zero buildings' construction will be required. Smart energy management systems in buildings and digitalisation (the Internet of Things) will change how buildings consume energy and even allow them to start to provide grid services through enhanced demand flexibility. Increasingly, the sector will be shifting to electric vehicles, meaning that charging can be done at home. Decentralised energy supply will enable local generation of electricity through solar PV systems or other decentralised energy systems, and increasingly storage, both electric and thermal, will be found in buildings. To achieve this shift, enabling regulation and permitting will be required, as will reducing administrative and bureaucratic barriers. Utilities increasingly will need to reinvent themselves towards energy services and leverage the new markets related to the information from the grids.

2 The IRENA (2020c) report "Innovation Outlook: Thermal Energy Storage" discusses the different thermal energy storage technologies and user cases for heating and cooling systems, and projects the development and innovation needs for the next decades.

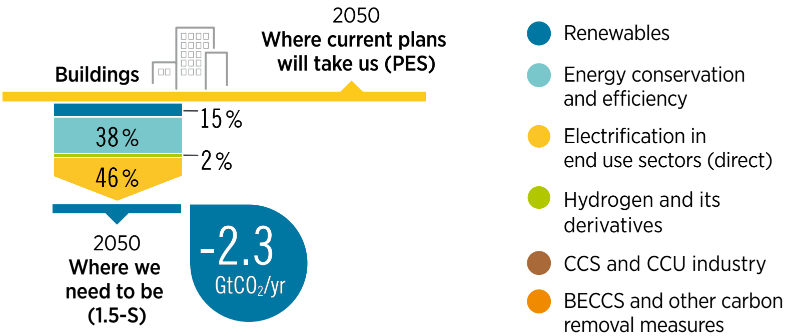
A.3.2 Opportunities for investors

To achieve the transformation envisioned in the buildings sector, USD 34 trillion will need to be invested in the sector and related infrastructure and supply by 2050. The bulk of investments are needed in building retrofits, smart home and energy efficiency investments, amounting to just under USD 1 trillion on average invested per year, or USD 29 trillion over the period to 2050. Investments to decarbonise energy supply for buildings require over USD 100 billion per year, or around USD 4 trillion to 2050. Meanwhile, key enabling technologies such as storage and smart meters will require annual investments of around USD 40 billion per year, or USD 1.2 trillion in total to 2050.

A.3.3. Carbon dioxide emissions

As a result of massive transition in the buildings sector, as outlined in the 1.5°C Scenario, energy-related CO_2 emissions decline 60% by 2030 and reach zero by 2050. Direct CO_2 emissions in the buildings sector account for 9% (3 Gt) of total energy-related CO_2 emissions in 2018. The result of this energy transition is that by 2050, CO_2 emissions in the sector would reach zero. Electrification measures would be responsible for 46% of total CO_2 reductions in the sector followed by energy efficiency improvements contributing to 38%, direct use of renewables for 15% and hydrogen for the remainder.

FIGURE A.6 Emission reductions in buildings in 2050



In buildings, the key solution is electrification contributing close to half of the CO_2 reduction needed, followed by energy efficiency.

References | **Annex A**

BNEF (2021), *Electric Vehicle Outlook 2020*, BloombergNEF, London, https://about.bnef.com/electric-vehicle-outlook.

BNEF (2020), "Battery pack prices cited below $100/kWh for the first time in 2020, while market average sits at $137/kWh", BloombergNEF, https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh.

Clean Sky 2 JU and FCH 2 JU (2020), *Hydrogen-powered aviation: A fact-based study of hydrogen technology, economics, and climate impact by 2050*, Clean Sky 2 Joint Undertaking and Fuel Cells and Hydrogen 2 JU, Brussels, www.fch.europa.eu/sites/default/files/FCH%20Docs/20200720_Hydrogen%20Powered%20Aviation%20report_FINAL%20web.pdf.

Deore. M., R. Kukreja and PN. Koti (2021), "OPINION: Why industrial decarbonization is an opportunity for India to fight climate change", Economic Times, https://energy.economictimes.indiatimes.com/news/power/opinion-why-industrial-decarbonization-is-an-opportunity-for-india-to-fight-climate-change/82052996.

EC (2020), "Renovation wave", European Commission, https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/renovation-wave_en.

Gielen D. and D. Saygin (2018), "Global industrial carbon dioxide emissions mitigation: Investigation of the role of renewable energy and other technologies until 2060", Working paper, Payne Institute for Public Policy, Colorado School of Mines, https://ljp6c3tnea61xd0wz1l33nmf-wpengine.netdna-ssl.com/wp-content/uploads/sites/149/2018/06/20180613_Gielen_WorkingPaper_web-1.pdf.

Gielen D., Y. Chen and P. Durrant (2021), "Decarbonising Industry is key to China's net-zero strategy", Energy Post, https://energypost.eu/decarbonising-industry-is-key-to-chinas-net-zero-strategy.

Gnadt, A.R. *et al.* (2019), "Technical and environmental assessment of all-electric 180-passenger commercial aircraft", *Progress in Aerospace Sciences*, Volume 105, pp. 1-30, https://doi.org/10.1016/j.paerosci.2018.11.002.

Government of the United Kingdom (2019), *Industrial decarbonisation strategy*, Crown Publishing, London, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/970229/Industrial_Decarbonisation_Strategy_March_2021.pdf.

IRENA (2021a), "Leaders summit: The energy transition priorities needed for a 1.5°C future", Expert Insights, 25 April 2021, International Renewable Energy Agency, Abu Dhabi, www.irena.org/newsroom/expertinsights/2021/April/Leaders-Summit-The-Energy-Transition-Priorities-Needed-for-a-1-5C-Future.

IRENA (2021b), *Innovation Outlook: Renewable Methanol*, IRENA, Abu Dhabi.

IRENA (2020a), *Reaching Zero with Renewables*, IRENA, Abu Dhabi.

IRENA (2020b), *Green Hydrogen Cost Reduction*, IRENA, Abu Dhabi.

IRENA (2020c), *Innovation Outlook: Thermal Energy Storage*, IRENA, Abu Dhabi.

IRENA (2020d), *Renewable Energy Policies in a Time of Transition: Heating and Cooling*, IRENA, Abu Dhabi.

IRENA (2019), *Hydrogen: A renewable energy perspective*, IRENA, Abu Dhabi.

IRENA (2017), *Electricity Storage and Renewables: Costs and Markets to 2030*, IRENA, Abu Dhabi.

Irie, R. (2020), "Global plug-in vehicle sales reached over 3.2 million in 2020", EV-volumes, Trollhättan, www.ev-volumes.com.

Moores, S. (2021), *The global battery arms race: Lithium-ion battery gigafactories and their supply chain*, Oxford Institute of Energy Studies, Oxford, www.oxfordenergy.org/wpcms/wp-content/uploads/2021/02/THE-GLOBAL-BATTERY-ARMS-RACE-LITHIUM-ION-BATTERY-GIGAFACTORIES-AND-THEIR-SUPPLY-CHAIN.pdf.

Pauschinger, T. (2016), "5 - Solar thermal energy for district heating", in Advanced District Heating and Cooling (DHC) Systems, R. Wiltshire (ed.), pp. 99-120, Woodhead Publishing, Cambridge, https://doi.org/10.1016/B978-1-78242-374-4.00005-7.

REN21 (2020), *Renewables 2020: Global Status Report*, Renewable Energy Policy Network for the 21st Century Secretariat, Paris. www.ren21.net/wp-content/uploads/2019/05/gsr_2020_full_report_en.pdf.

Saygin, D. and D. Gielen (2021), "Zero-emission pathway for the global chemical and petrochemical sector", *Energies*, Vol. 14, No. 13, pp. 3772, https://doi.org/10.3390/en14133772.

Schäfer, A.W. et al. (2019), "Technological, economic and environmental prospects of all-electric aircraft", *Nature Energy*, Vol. 4, pp. 160-166, www.nature.com/articles/s41560-018-0294-x.

Trahey, L. et al. (2019), "Energy storage emerging: A perspective from the Joint Center for Energy Storage Research", *Proceedings from the National Academy of Sciences*, Vol. 117, No. 23, pp. 12550-57, www.pnas.org/content/117/23/12550.

ANNEX B

SOCIO-ECONOMIC FOOTPRINT

Annex B.1 Socio-economic implications of varying carbon pricing from optimum levels

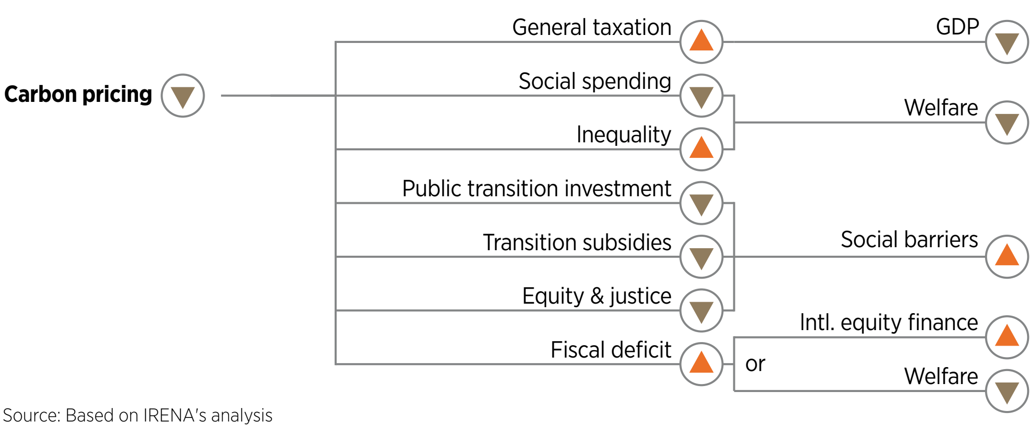
Modifying the level of carbon pricing from its optimal value- through its contribution to government fiscal balances - for a given climate goal and climate policy basket may have important socio-economic implications. Increasing carbon pricing above its optimal value will exacerbate its regressive effects, triggering negative impacts on welfare and economic activity, potentially creating transition barriers.

Figure x illustrates the potential consequences of reducing carbon pricing from its optimal value. Not allowing deficit spending can have:

1. a negative impact on GDP, if governments decide to increase general taxation; and/or
2. a negative impact on welfare and exacerbate inequality and/or create energy transition barriers, if governments decide to reduce social spending.

Alternatively, deficit spending could increase as has been the case historically in response to crises (most recently demonstrated by the COVID-19 pandemic). However, given fiscal constraints in the Global South to address social needs and the demands of the energy transition, it would require strong international collaboration to marshal the necessary resources.[1]

FIGURE B.1 Potential transition implications of sub-optimal carbon pricing



Source: Based on IRENA's analysis

1 Specially those without monetary sovereignty or with high dependence on foreign exchange rates.

Annex B.2 Welfare index methodology

IRENA's Energy Transition Welfare Index captures five dimensions namely, economic, social, environmental, distributional, and energy access. This section outlines the indicators comprising each dimension and discusses the methodology followed for the computation of the welfare index.

Indictors of each welfare dimension

Economic dimension

The economic dimension addresses the contribution form sustainable economic activity to welfare, and it is informed by two indicators: per capita consumption and investment, and non-employment.[2]

1. Consumption reflects disposable income, and hence can be used as a proxy for increases in current well-being, whereas investment supports future well-being. Acknowledging the decreasing marginal returns of consumption to welfare, a logarithmic scale is used, and a sufficiency limit has been introduced,[3] beyond which additional consumption does not contribute any further. Likewise, an aspirational goal of minimum consumption has been introduced to account for poverty lines.

2. Employment, as means for income generation, contributes to the welfare of current and future generations. The economic dimension of the welfare index includes the non-employment indicator, which tracks the share of the working age population that is neither employed nor young and in education.

Social dimension

The social dimension addresses the use of public resources to provide social value and address externalities faced by society. It uses two indicators: per capita public expenditures aimed to increase social value; and per capita health impacts from pollution.

1. The per capita social public expenditure includes spending on education, health, and social welfare, together with transition-related public investment and budgets related to climate policies. The associated index includes a minimum aspirational goal to acknowledge a basic contribution from public expenditure to welfare.

2. The health impact indicator is the per capita health costs linked to energy system-related air pollution (indoors and outdoors), which emphasises the relevance of living in a healthy, unpolluted environment for people's well-being.

2 The state of not having paid work, excluding young people (age group from 15 to 24 years) getting an education. Non-employment is hence calculated as the share of the working age population (age group from 15 to 64 years) that is neither employed nor under education while belonging to the 14-24 age group. Non-employment is used instead of the unemployment or employment metrics because its more comprehensive gauging of the social implications of paid work, which is the main goal of a welfare index. Indeed, while unemployment and employment are evaluated as shares of the labour force, non-employment is defined on the basis of the whole working age population (not only the part of it belonging to the labour force), and hence beyond the short-term lack of paid work also captures the long-term lack of paid work (which is excluded from the labour force).

3 It should be noted that countries/regions exceeding this sufficiency limit are not penalised in terms of the welfare index. They just reach the maximum value (100%) of the corresponding indicator's index.

Environmental dimension

The environmental dimension addresses the sustainability of socio-economic activity within planetary boundaries. It is informed by two indicators: climate change and the use of natural resources.

1. The impacts from climate change on welfare are captured by vulnerability adjusted cumulative[4] CO_2 emissions.[5] The vulnerability adjustment acknowledges that countries and regions differ both by multi-sectoral propensity to be negatively impacted by climate change (exposure, sensitivity, adaptive capacity) and their readiness for adaptation (across all economic, governance and social dimensions).
2. The resource use indicator is per capita materials consumption[6] (excluding fossil fuels) and includes a developmental allowance[7] linked to the planetary sustainability boundary.

Distributional dimension

Distributional aspects, receive increasing public attention, and are bound to play an important role in the transition, either as barriers or enablers. To gain insights into the transition dynamics affecting inequality and how policy frameworks can address these, IRENA has included a distributional dimension in its welfare index.

The distributional dimension has two indicators:

1. Within countries/regions (intra) inequality.
2. Between countries/regions (inter) inequality.

Both income and wealth inequality are tracked. Each one of the indexes associated to these indicators is constructed as the arithmetic average of income and wealth inequality indexes. The indicator used is the quintile ratio: the ratio of income/wealth from the highest quintile (20% of population) to the income/wealth from the lowest quintile (20% of population) of the income/wealth distributions.

The inter-distributional index (between countries) is common for all countries/regions, while the intra-distributional index (within countries/regions) is specific to each country/region. In the case of global results, the intra distributional indicator corresponds to the distribution of global citizens.

4 Cumulative emissions are evaluated from 2021 to 2050 (the scenarios time span)

5 Includes all CO_2 emissions (energy-related, industrial process and LULUCF)

6 Currently evaluated as Domestic Material Consumption (DMC).

7 Such that if the per capita materials consumption is lower than this allowance the Index is 100% and hence the materials consumption does not negatively impact the IRENA's Energy Transition Welfare Index.

8 Access to clean cooking is used here as a proxy to overall energy access.

Access dimension

The access dimension addresses energy access and provides the visibility needed to track progress in this fundamental dimension, which if not specifically addressed is often overlooked.

The access dimension has two indicators: share of population without basic energy access; and progress along the energy access ladder.

1. The index associated to the share of population without energy access includes the aspirational goal of reaching full basic energy access.

2 The indicator used to measure progress along the energy access ladder[9] is per capita total final energy consumption. The index introduces a sufficiency limit, such that once per capita total final energy consumption reaches this sufficiency limit, the index achieves a maximal value of 1. In order to capture the effect of energy efficiency improvements over time, the sufficiency limit includes an efficiency modulation factor that adjusts it with time.

Methodology for welfare index computation

Welfare index indicators are normalised into indicator indexes using goalposts and include a directional parameter that aligns indicator index with welfare impact. Hence, indicator indexes are all bounded by zero and one, and increasing index values have positive impacts on welfare[10]. Sufficiency thresholds, thresholds on bad performance, minimum aspirational goals and development allowances are included into the indicator indices' formulation.

The combination of indicators into dimensional indexes and that of dimensional indexes into the welfare index uses a modified geometric mean to limit substitutability while addressing zeroing and masking effects.

Several criteria have been applied for choosing goalposts:

a) Invariance across simulations/analyses: In this case, the MAX and MIN are chosen to remain invariant across simulations, and hence results from different simulations can be compared. This could lead to the indexes series for a given analysis, while being within in the {0,1} range, not occupying this range completely.

8 Access to clean cooking is used here as a proxy to overall energy access.

9 Energy poverty is partly addressed by this indicator and complemented by the distributional dimension.

10 To illustrate, decreasing emissions would contribute positively to welfare as would increasing energy access.

b) Introducing **sufficiency conditions**. This applies to the MAX of an indicator that when increasing improves welfare and acknowledges the fact that beyond a certain value further increases from this indicator does not improve the considered welfare dimension. An example is in the energy access dimension for the indicator showing progress through the access ladder: beyond the sufficiency level, access has been achieved and the indicator does not improve further.[11] Application of the sufficiency criteria requires modifying the index formulation by capping the indicator at MAX.[12]

c) Introducing a **threshold on bad performance**. This applies to the MAX of an indicator that when increasing reduces welfare and introduces a bad performance threshold from where a zero value for the index is obtained. In that way the index does not capture further welfare implications of bad performance beyond the threshold, but it better captures the differences between countries performing below the threshold. An example is wealth inequality when measured through a quintile ratio, where in some regions is so high (infinity) that without introducing the threshold would completely dilute the index in all other countries/regions. This applies also to other indicators such as material consumption too high compared with planetary boundary and health impacts too high for social acceptability.

d) Introducing a **minimum aspirational goal**. This applies to the MIN of an indicator that when increasing improves welfare. When the indicator falls below the MIN, the index becomes zero (not achieving minimum aspirational goal in this dimension). An example is when consumption and investment falls below the poverty line. Application of the minimum aspirational goal requires modifying the index formulation by limiting the lower value of the indicator to MIN :

e) Introducing a **development allowance**. This applies to the MIN of an indicator that when increasing reduces welfare, but there is a threshold below which it could maintain sustainable economic activity. An example is materials consumption. If kept enough below a sustainable limit, it can be used for increasing welfare and hence should not penalise the welfare index. Application of the development allowance requires modifying the index formulation by limiting the lower value of the indicator to MIN:[14]

11 Countries are not penalised for going beyond this sufficiency limit, but no additional credit is provided in the concerned welfare dimension (index at its maximum value of I=1).

12 Note that for all indexes MAX acts as a cap for the Indicator (avoiding indexes outside the 0 – 1 range). The difference here is that MAX is intentionally set to a value lower than the expected maximum in the indicator's series range.

13 Note that for all indexes MIN acts as a lower limit for the indicator (avoiding indexes outside the 0 – 1 range). The difference here is that MIN is intentionally set to a value higher than the expected minimum in the indicator's series range.

14 Note that for all indexes MIN acts as a lower limit for the indicator (avoiding indexes outside the 0 – 1 range). The difference here is that MIN is intentionally set to a value higher than the expected minimum in the indicator's series range.

Indicator's goalposts

Table B.1 presents the goalposts' used for each indicator. The table also indicates whether an upper or lower limit to the possible range has been imposed because of sufficiency, threshold on bad performance, aspirational goal or development allowance.

TABLE B.1 Goalposts for the indicators in IRENA's Energy Transition Welfare Index

DIMENSION	INDICATOR	UNITS	MIN	MAX	UPPER LIMIT	LOWER LIMIT	DIR.
Economic	Consumption and Investment	USD/ person-year	700	45 000	Yes	Yes	0
	Non-Employment	%	0	70	-	-	1
Social	Social expenditure	USD/ person-year	150	30 000	-	Yes	0
	Health Impact	USD/ person-year	0	1 000	Yes	-	1
Environmental	CO_2 emissions[15]	$GtCO_2$	0	2361	-	-	1
	Materials consumption	Tones/ person-year	2.5	12.5	Yes	Yes	1
Distributional[16]	Within country/ region	-	1	80 – IQR 160 – WQR	Yes	-	1
	Between countries	-	1	20 – IQR 40 – WQR	Yes	-	1
Access	Share of population without access	%	0	100%	-	-	1
	Progress in access ladder[17]	kWh/p-d	0	20	Yes	-	0

Based on IRENA's analysis

15 Cumulative until 2050.

16 The quintile ratio (QR), as the ratio from the highet quintile to that of the lowest quintile, is the indicator used to measure distributional aspects. The indicator is applied to income distribution (IQR) and to wealth distribution (WQR).

17 The MAX in this indicator is also affected by an efficiency modulation function which captures the effect of improving efficiency with time.

Producing dimensional and overall welfare index

Combining indicator's indices to produce a dimensional index, or dimensional indices to produce the welfare index, requires a methodology to average the different indices.

IRENA's Energy Transition Welfare Index methodology uses arithmetic or geometric averaging depending on whether full substitutability between the indices being averaged is considered appropriate or not for the purpose of measuring overall welfare. Except for the case of combining income and wealth inequality in the distributional dimension, all other averaging uses a geometric mean[18] to limit substitutability between different indices.[19]

However, the geometric mean presents two inconvenient characteristics for the welfare index:

- Zeroing effect: when one or more dimensional indexes are zero, the geometric mean becomes zero.
- Masking effect: very low values in one or more dimensions produce a very low geometric mean, masking the evolution in the other dimensions.

IRENA's welfare index uses a modified geometric mean that addresses the zeroing and masking effects.

18 Besides the reduced substitutability, the geometric mean offers other advantages to the welfare index: Ensures that a 1% decline in the index in any dimension has the same impact on the IRENA's Energy Transition Welfare Index; Sufficiency components become neutral once the sufficiency threshold has been achieved; It is the only mean for which the mean of a quotient is the quotients of the means, and hence the ranking of the results is independent on what is used as a reference.

19 Low achievement in one index/dimension is not linearly compensated for by a higher achievement in another index/dimension.

Annex B.3 Data tables

Employment

TABLE B.2 **Energy sector jobs for the 1.5°C Scenario and differences with PES over time, global results.**

			2021[20]	2030	2050
Energy sector	absolute	million jobs	91.0	136.5	121.8
	difference with PES	million jobs	-	25.8	8.0
		relative	-	23.3%	7.0%
Transition-related	absolute	million jobs	52.5	106.5	95.8
	difference with PES	million jobs	-	39.8	28.3
		relative	-	59.6%	42.0%
Fossil fuels	absolute	million jobs	37.9	29.4	25.8
	difference with PES	million jobs	-	-13.9	-20.0
		relative	-	-32.1%	-43.7%

20 2021 estimates are obtained through a calibrated macroeconomic model based on investments associated with the PES scenario. It should be noted that the jobs reported here for the energy sector go beyond the traditional categories for this sector (fossil fuels, electricity generation, bioenergy) and besides nuclear, also include energy efficiency, energy flexibility, power grids, hydrogen value-chain, and heat pumps-related jobs.

Employment

TABLE B.3 Renewable energy jobs by technology in the 1.5°C Scenario and differences with the PES, global results.

			2021	2030	2050
Solar	absolute	million jobs	5.52	17.32	19.90
	difference with PES	million jobs	-	10.01	9.64
		relative	-	137%	94%
Bioenergy	absolute	million jobs	5.34	11.11	13.67
	difference with PES	million jobs	-	6.02	7.72
		relative	-	118%	130%
Wind	absolute	million jobs	1.98	5.57	5.48
	difference with PES	million jobs	-	3.05	2.11
		relative	-	121%	62%
Hydro	absolute	million jobs	3.52	3.32	3.70
	difference with PES	million jobs	-	0.42	1.05
		relative	-	14%	40%
Geothermal	absolute	million jobs	0.14	0.30	0.23
	difference with PES	million jobs	-	0.12	0.02
		relative	-	72%	7%
Tidal/Wave	absolute	million jobs	0.002	0.18	0.37
	difference with PES	million jobs	-	0.18	0.31
		relative	-	7 907%	472%

Employment

TABLE B.4 Renewable energy jobs by segment of value chain in the 1.5°C Scenario and differences with the PES, global results.

			2021	2030	2050
Construction & Installation	absolute	million jobs	4.5	12.0	14.2
	difference with PES	million jobs	-	6.7	5.1
		relative	-	126%	57%
Manufacturing	absolute	million jobs	4.3	11.0	8.7
	difference with PES	million jobs	-	6.2	5.6
		relative	-	131%	178%
O&M	absolute	million jobs	3.1	5.4	9.3
	difference with PES	million jobs	-	1.5	3.0
		relative	-	38%	48%
Biofuel supply	absolute	million jobs	4.6	9.4	11.2
	difference with PES	million jobs	-	5.4	7.1
		relative	-	135%	176%

TABLE B.5 Energy sector jobs by educational requirement in the 1.5°C Scenario and differences with the PES, global results.

			2021	2030	2050
Primary	absolute	million jobs	24.1	47.3	60.7
	difference with PES	million jobs	-	8.4	1.0
		relative	-	22%	2%
Secondary	absolute	million jobs	37.8	34.8	44.8
	difference with PES	million jobs	-	8.6	4.8
		relative	-	33%	12%
Tertiary	absolute	million jobs	29.1	54.5	16.2
	difference with PES	million jobs	-	8.8	2.2
		relative	-	19%	16%

Welfare

TABLE B.6 Welfare and dimensional indexes for 1.5-S and PES, as well as the relative difference between both, for 2030 and 2050, global results.

DIMENSION	2030			2050			COMMENT
	PES INDEX	1.5-S INDEX	DIFFER-ENTIAL	PES INDEX	1.5-S INDEX	DIFFER-ENTIAL	
Economic	0.642	0.645	+0.4%	0.655	0.656	+0.2%	Small improvement aligned with improvements of 1.5-S over PES in GDP and employment.
Social	0.153	0.187	+23%	0.218	0.268	+23%	Through improved public health, makes a significant contribution to the increase from PES to 1.5-S, but remains low and hence provides significant potential for improving the overall welfare index.
Environ-mental	0.547	0.711	+30%	0.474	0.614	+30%	Mainly driven by the mitigation of CO_2 emissions.
Distribution	0.018	0.052	+186%	0.157	0.154	-2%	Low index values in both PES and 1.5-S reflect the persistence of high inequalities irrespective of changes to the global energy landscape.
Access	0.857	1	+17%	0.934	1	+7%	Both scenarios above sufficiency limit, but PES still without full basic energy access by 2050.
Welfare	**0.253**	**0.344**	**+36%**	**0.399**	**0.442**	**+11%**	Improvements in welfare index (1.5-S over PES) are higher than for GDP or employment. But low index values indicate room for improvement in welfare.

Welfare

TABLE B.7 Economic index and its indicator's indexes for 1.5°C Scenario and PES, for 2030 and 2050, global results.

INDICATOR	2030			2050			COMMENT
	PES INDEX	1.5-S INDEX	DIFFER-ENTIAL	PES INDEX	1.5-S INDEX	DIFFER-ENTIAL	
Consumption and Investment	0.645	0.643	-0.3%	0.767	0.767	0%	Almost neutral role because of 1.5-S policy to earmark revenues for transition-related government spending. Per capita consumption and investment increases over time in both scenarios, almost doubling per-capita value.
Non-employment	0.639	0.647	+1%	0.559	0.561	+0.4%	Positive impact of the transition on non-employment. Non-employment increases over time in both scenarios.
Economic Index	0.642	0.645	+0.4%	0.655	0.656	+0.2%	Improvement of 1.5-S over PES mainly driven by non-employment improvements. Index reaches a minimum value around 2030, consequence of the balance in trends from its two indicators.

Welfare

TABLE B.8 Social index and its indicators' indexes for 1.5°C Scenario and PES, for 2030 and 2050, global results.

INDICATOR	2030			2050			COMMENT
	PES INDEX	1.5-S INDEX	DIFFER-ENTIAL	PES INDEX	1.5-S INDEX	DIFFER-ENTIAL	
Social expenditure	0.047	0.051	+9%	0.081	0.085	4%	Social spending improves over time in both scenarios, almost doubling in per-capita terms. However, the social spending index value remains very low. Hence, there is significant room to improve the welfare index by increasing social spending.
Health impact	0.483	0.669	+39%	0.571	0.827	+45%	Health impacts reduce over time in both scenarios, but at a much higher rate in the 1.5-S reflecting the huge benefits that the energy transition brings about by eliminating outdoor and indoor air pollution. Under the PES, by 2050, global average health impacts still amount to a staggering 2019 USD 430/person-year.
Social Index	0.154	0.189	+23%	0.218	0.268	+23%	Improves over time for both scenarios. The low index value is consequence of low social spending.

Welfare

TABLE B.9 Environmental index and its indicators' indexes for 1.5°C Scenario and PES, for 2030 and 2050, global results.

INDICATOR	2030			2050			COMMENT
	PES INDEX	1.5-S INDEX	DIFFER-ENTIAL	PES INDEX	1.5-S INDEX	DIFFER-ENTIAL	
CO_2 emissions	0.446	0.754	+69%	0.446	0.754	+69%	Constant over time because the scenario's cumulative emissions is the indicator impacting climate change. Strong improvement of 1.5-S over PES because of ambitious mitigation effort.
Materials consumption	0.671	0.671	0%	0.504	0.501	-0.6%	Materials consumption increasing for both scenarios due to increasing aggregated economic activity. During the first decade, the GDP stimulus in 1.5-S leads to higher material consumption than PES.
Environmental Index	0.547	0.711	+30%	0.474	0.614	+30%	The index deteriorates over time consequence of the increase in materials consumption. The positive improvement of 1.5-S over PES is dominated by the mitigation of CO_2 emissions.

Welfare

TABLE B.10 Distributional index and its indicators' indexes for 1.5°C Scenario and PES, average 2021-2050, global results.

INDICATOR	AVERAGE 2021 - 2050			COMMENT
	PES INDEX	1.5-S INDEX	DIFFER-ENTIAL	
Intra-inequality	0.123	0.176	+44%	The index improves over time. The wealth component drags the index down, attenuating the improvements in income. Lump-sum payments play a significant role in the 1.5-S over PES difference.
Inter-inequality	0.076	0.091	+20%	The index improves over time, with both its wealth and income components contributing to this. International cooperation plays a role in the improvement of 1.5-S over PES, more strongly felt during the first decade.
Distributional Index	0.088	0.121	+37%	High improvement of 1.5-S over PES, consequence of the introduced policy elements addressing inequality. But index values are very low, indicating a huge room to improve welfare by strengthening policy action addressed at improving the distributional dimension.

TABLE B.11 Access index indicator's contributions for 1.5S and PES by 2050, global results.

INDICATOR	2030			2050			COMMENT
	PES INDEX	1.5-S INDEX	DIFFER-ENTIAL	PES INDEX	1.5-S INDEX	DIFFER-ENTIAL	
Basic access	0.735	1	+36%	0.873	1	+15%	The 1.5S reaches universal basic access by 2030, while the PES is not there even by 2050.
Energy sufficiency	1	1	0%	1	1	0%	Globally, both scenarios are above the sufficiency limit. But this average hide energy inequalities between countries.
Access index	0.857	1	+17%	0.934	1	+7%	Index improves over time for both scenarios, driven by progress in universal basic access.

IRENA

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