IRENA

International Renewable Energy Agency

WORLD ENERGY TRANSITIONS OUTLOOK 2024

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 2024

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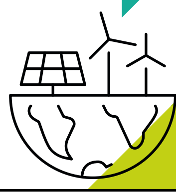

The *World Energy Transitions Outlook* outlines a vision for the transition of the energy landscape to reflect the goals of the Paris Agreement, presenting a pathway for limiting global temperature rise to 1.5°C and bringing CO_2 emissions to net zero by mid-century.

The report builds on two of IRENA's key scenarios to capture global progress toward meeting the 1.5°C climate goal:

Planned Energy Scenario

The **Planned Energy Scenario** is the primary reference case for this study, providing a perspective on energy system developments based on governments' energy plans and other planned targets and policies in place at the time of analysis, with a focus on G20 countries.

1.5°C Scenario

The **1.5°C Scenario** describes an energy transition pathway aligned with the 1.5°C climate goal 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 to meet the 1.5°C goal.

FOREWORD

As leaders meet for COP29 in Baku, IRENA's *World Energy Transition Outlook* demonstrates that the global energy transition remains off course, undermining our ability to meet the 1.5°C climate goal agreed at COP21 in Paris almost a decade ago. It is not too late, but an immediate course correction is needed to bring the world back on track.

To achieve this, the world must overcome structural and systemic barriers that continue to impede the progress of the energy transition. This requires, *inter alia*, modernising and expanding transition infrastructure, including grids; establishing regulatory frameworks and market designs fit for the age of renewables; and delivering the institutional and human resource capacities required to support the energy transition.

The Outcome of the First Global Stocktake at COP28 called on all Parties to the UNFCCC to triple renewable power and double energy efficiency by 2030, providing new momentum to the transition. As the custodian agency tasked with reporting on these goals, IRENA has identified some positive trends, including the significant acceleration in the deployment of renewable power capacity in 2023.

However, further growth is needed to triple renewable power capacity to 11 000+ gigawatts by 2030; investments in renewable power, grids and flexibility, energy efficiency and conservation must increase dramatically to meet the renewable energy and efficiency goals, totalling USD 31.5 trillion in 2024-2030.

The next round of Nationally Determined Contributions to the Paris Agreement in 2025 (NDC 3.0) provides the last opportunity this decade for countries to step up their stated ambitions and ensure their plans and policies are aligned with the capacity additions required to meet the 1.5°C goal.

Renewables investment and deployment remain concentrated in relatively few countries; more attention is therefore needed to ensure the energy transition is truly global. This will require more international collaboration to channel funding for the transition in the global South, highlighting the importance of efforts to establish the New Collective Quantified Goal (NCQG) for climate finance at COP29.

The financing required is considerable; inevitably, much of this will need to come from the G20 – the world's largest economies and biggest emitters. Under tight fiscal conditions, a further option for revenue collection to fund a just transition could be collaborative international financing based on wealth taxation, as championed by this year's G20 Brazilian Presidency.

More effective energy planning can stimulate renewable energy investment by reducing risks and transaction costs, thereby establishing conditions conducive to attracting private capital. The Global Coalition on Energy Planning (GCEP) established by the G20 Brazilian presidency, underscores the critical role of energy planning in accelerating the energy transition, as also emphasised by IRENA's Global Long-Term Energy Scenarios (LTES) Network and LTES for Clean Energy Transition initiative.

The growing use of artificial intelligence (AI) presents both opportunities and challenges for the energy transition. The proliferation of AI will clearly contribute to electricity demand, but may also rationalise demand in other sectors by introducing efficiencies, and must be seen in the context of the need for broader electrification of end-use sectors in line with a pathway compatible with net-zero by mid-century.

The overriding goal remains to deliver a just and equitable global energy transition built upon renewable power, widespread electrification and increasing energy efficiency. In this regard, we must grasp the opportunity to agree new terms to boost climate finance for emerging countries and developing economies at COP29 to ensure the transition leaves no one behind.

Francesco La Camera
Director-General, IRENA

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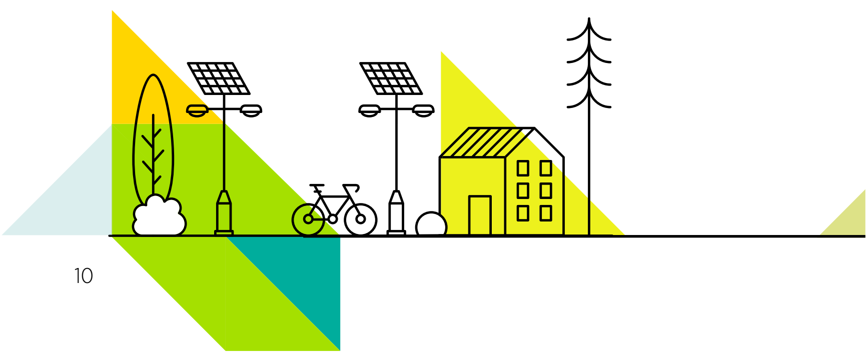

ABBREVIATIONS

CAGR	compound annual growth rate
CBDR-RC	Common but Differentiated Responsibilities and Respective Capabilities
CO_2	carbon dioxide
COP	Conference of the Parties to the United Nations Framework convention on Climate Change
CSP	concentrated solar power
DH	district heating
DRE	decentralised renewable energy
EMDEs	emerging markets and developing economies
EU	European Union
EU-27	27 member countries of the European Union
EV	electric vehicle
FID	final investment decision
G20	Group of 20
GDP	gross domestic product
Gt	gigatonne
GW	gigawatt
GWh	gigawatt hour
GWEC	Global Wind Energy Council
KPI	key performance indicator
kWh	kilowatt hour
LCOE	levelised cost of electricity
LDES	long-duration energy storage
LT-LEDS	long-term low-emission development strategies
LTES	long-term energy scenario
Mt	million tonnes
NCQG	New Collective Quantified Goal
NDC	Nationally Determined Contribution
OECD	Organisation for Economic Co-operation and Development
PES	Planned Energy Scenario
PV	photovoltaic
PWh	petawatt hour
RCI	Responsibility and Capability Index
SDES	short-duration energy storage
SDG	Sustainable Development Goal
STES	short-term energy storage
tCO_2eq	tonne of carbon dioxide equivalent
TFEC	total final energy consumption
TPES	total primary energy supply
TW	terawatt
TWh	terawatt hour
UNFCCC	United Nations Framework Convention on Climate Change
VRE	variable renewable energy

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EXECUTIVE SUMMARY

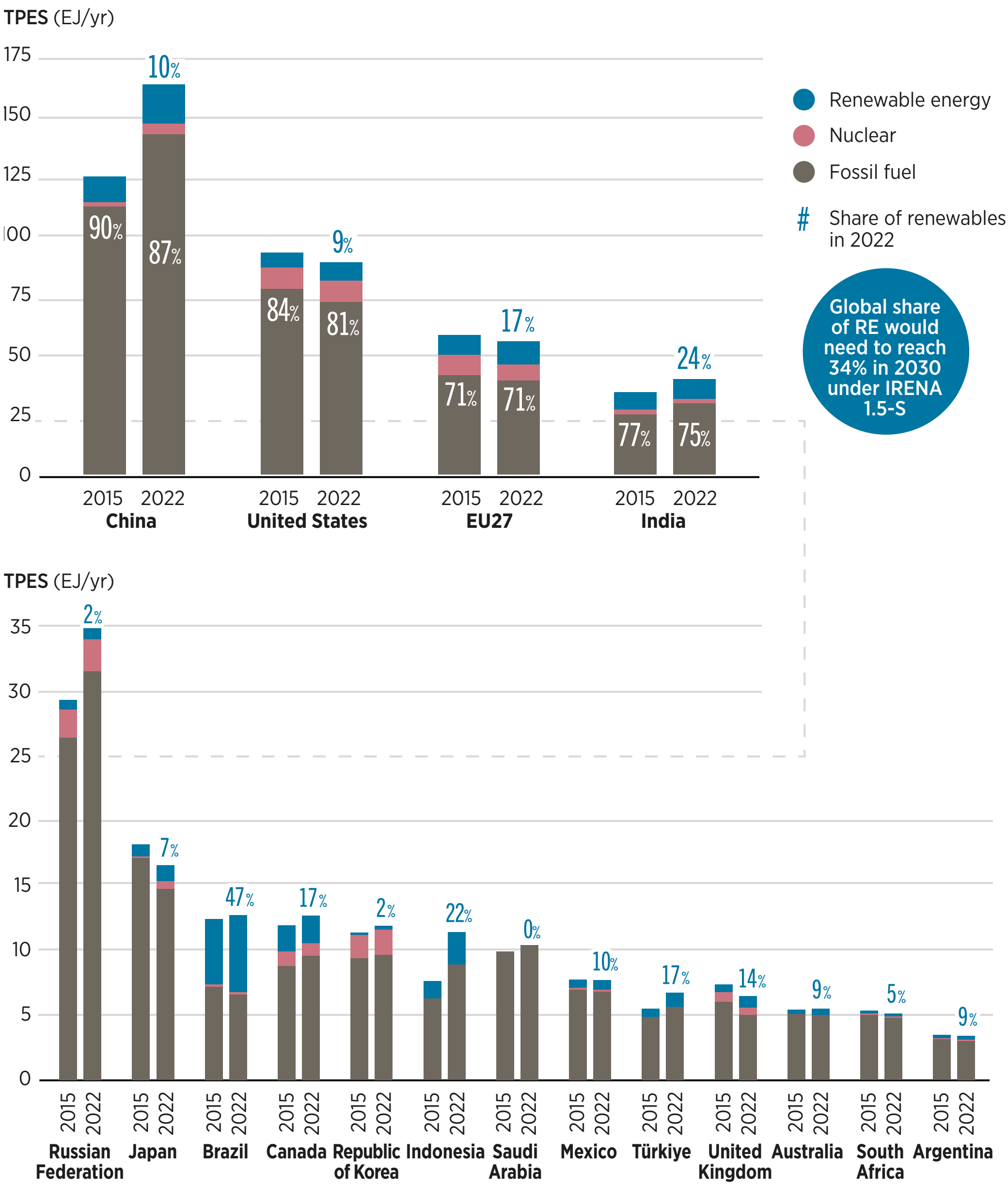
While 2023 saw record growth in renewables deployment in the power sector, progress has been geographically uneven, and lacklustre for other sectors and alternative energy carriers. To meet the 1.5°C climate target, the world must achieve net-zero carbon dioxide (CO_2) emissions by 2050, which will require a systemic transformation of the global energy system. Despite the commitments made at COP28 in Dubai in 2023, and new initiatives from the G20 and G7, the energy transition remains off track. Fossil fuels continue to dominate the energy mix in major economies – the world's largest CO_2 emitters (Figure S1) – and each year the chances of meeting the goals of the Paris Agreement become increasingly remote.

A significant gap remains between recent high-level political announcements and countries' actual plans and policies, both in terms of renewable capacity additions and investments. Current national plans and targets are set to deliver only half of the required growth in renewable power by 2030. While renewable power deployment has exceeded expectations in some countries, other aspects of the energy transition are lagging behind. Lack of progress on energy access under Sustainable Development Goal 7 (SDG7) demonstrates that more needs to be done to ensure the transition is just and inclusive. Many countries in the global South still struggle to attract investment, despite worldwide investments in renewables reaching a new record in 2023.

The New Collective Quantified Goal (NCQG) for climate finance to be agreed at COP29, and NDC 3.0 submission process in 2025, provide unique opportunities to bring the world back to a 1.5°C pathway. Agreement on a robust NCQG is important for supporting investments in the energy transition in the global South. More widespread availability of financial support will allow countries to step up their NDC 3.0 ambitions. The world's largest emitters – the G20 countries – also need to enhance their own NDCs. These should match commitments to triple renewable power capacity and double the rate of energy efficiency improvement by 2030, as well as the longer-term ambition to decarbonise all sectors.

International collaboration is essential for bringing about a just and inclusive energy transition. Together with specific policies to direct financial resources towards social value creation, there is significant potential for increased international collaboration to improve the global welfare outcomes of the transition. The G20, as the world's largest emitters and richest countries, must therefore increase their commitments to international collaboration.

FIGURE S1 **Total primary energy supply in G20 nations, by energy type, 2015 and 2022**



Note: Historical data from (IEA, 2024b); Renewables include hydro, solar, wind, bioenergy, geothermal, and marine energy; TPES = total primary energy supply; EJ = exajoule; yr = year; RE = renewable energy; 1.5-S = IRENA's 1.5°C scenario.

Tripling renewables and doubling energy efficiency: Key milestones for 2030

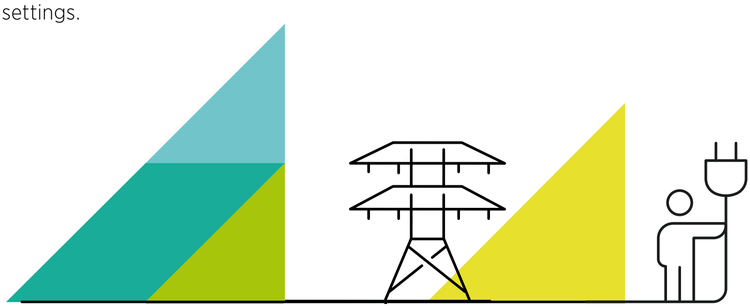
Tripling installed renewable power capacity and doubling the rate of energy efficiency improvement by 2030 are crucial milestones in the pursuit of the 1.5°C target. The Outcome of the First Global Stocktake at COP28 – known as the UAE Consensus – called on all Parties to the United Nations Framework Convention on Climate Change (UNFCCC) to contribute to global efforts in this regard. Complemented by the preceding pledge by more than 130 countries at COP28 to meet these goals, the UAE Consensus provided new impetus to global efforts to mitigate climate change by accelerating the energy transition.

2023 saw record deployment of new installed renewable power capacity and the highest ever annual increase in solar photovoltaic (PV). In 2023, renewable power capacity grew by 473 gigawatts (GW) (of which 347 GW was solar PV), compared to the 298 GW of renewables (146 GW of solar PV) added in 2022. China, the European Union and the United States accounted for 83% of the additions in 2023. The leading role played by solar PV is expected to continue for the rest of the decade, thanks to its sustained cost-competitiveness, manufacturing over-capacity and flexible scalability.

Deployment must increase more rapidly to achieve the tripling target. The first edition of IRENA's annual tracking report – as custodian of the renewable energy and energy efficiency goals established in the UAE Consensus – finds that average annual additions of 1044 GW will be required to triple installed renewable capacity to 11.2 terawatt (TW) by the end of the decade – representing 16.4% compound annual growth between 2024 and 2030. Expanding renewables in regions and countries outside leading markets, and scaling up renewables other than solar PV, are two key priorities for meeting decarbonisation goals. Intensive international collaboration is needed to deliver on the 2030 target and, more importantly, to achieve net-zero emissions by 2050.

Progress in energy efficiency is also lacking. Achieving the 4% energy intensity improvement rate required to meet the doubling target will depend on sufficient energy efficiency investment and increased electrification across multiple sectors, including transport, buildings and industry. Progress on key indicators has been mixed; while electric cars accounted for a record 18% of total car sales in 2023, the sales of heat pumps – vital for decarbonising the heating sector – fell by 3%.

The world is also in danger of missing another key target in 2030 – achieving universal access to affordable, reliable sustainable and modern energy under SDG7. Around 685 million people lack access to electricity and 2.1 billion continue to cook with polluting fuels and technologies. At the current pace of progress, an estimated 660 million people in developing countries will remain without access to electricity – and 1.8 billion people without access to clean cooking – in 2030, the majority of whom live in sub-Saharan Africa. Renewables could provide a cost-effective solution to these access needs, especially in off-grid settings.



The pathway to 2050

Achieving the 1.5°C target by 2050 is both technically feasible and economically viable. IRENA's decarbonisation pathway comprises a combination of end-use sector electrification and renewable power generation, energy efficiency, direct use of renewables (including biofuels), clean hydrogen, and carbon capture and storage (CCS) – including with bioenergy (BECCS) – and other removals. It requires increased commitment, policy support, investment at scale and project development at speed.

To achieve these aims, the world must overcome structural and systemic barriers that continue to impede the progress of the energy transition. This requires, inter alia, modernising and expanding transition infrastructure, including grids; establishing regulatory frameworks and market designs fit for the age of renewables; and delivering the institutional and human resource capacities required to support the energy transition.

The emissions gap remains significant. Aligning energy planning with climate strategy development may help to close this gap. In many countries, however, energy planning processes and climate policy development should be better integrated to avoid uncertainties among stakeholders regarding policy direction and investment decisions.

By 2050, a deep transformation of the power and end-use sectors is required to enable the high shares of renewable energy required by the transition. Under IRENA's 1.5°C Scenario, 91% of global electricity supply would come from renewable energy sources by 2050. Much of this would be from variable renewable energy (VRE) sources, with solar PV and wind contributing around 70%. Electricity would account for 52% of final energy consumption by 2050. Achieving even higher shares of renewables is possible but challenging in the current technological and regulatory context.

Enabling high shares of renewables in the power system

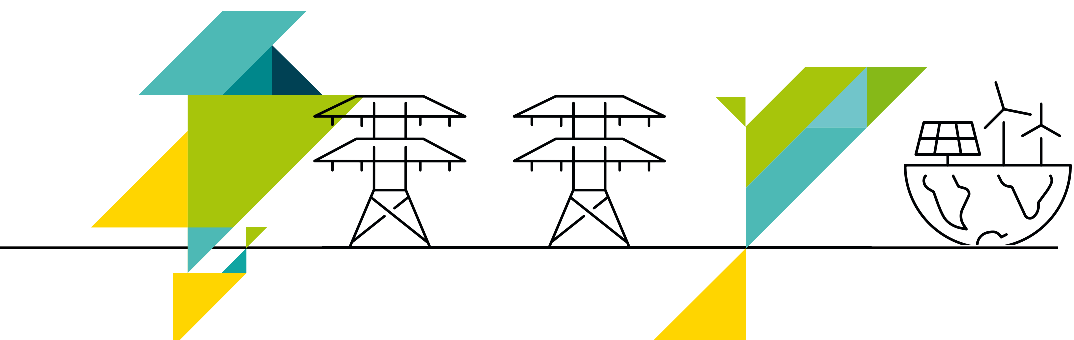
Several countries and regions have set ambitious targets to achieve 100% renewables in their power systems. Aiming for 100% renewable power, whilst also maintaining continuous and reliable energy supply, can be less challenging in power systems with abundant dispatchable renewable resources than in systems relaying on VRE. However, affordable dispatchable renewable resources are not widely available worldwide. Adding grid flexibility, particularly to the extent required for ensuring supply security in a 100% renewable energy system, can be economically costly.

Flexibility is key for enabling high shares of VRE and extensive electrification. Flexibility requires swift and carefully-planned grid infrastructure upgrades, modernisation and expansion on a significant scale. Enhanced power system operation, interconnections for cross-border trade, and various forms of storage capacity (electrical, thermal, *etc.*) are key components for increased system flexibility.

While a range of technical solutions are available to accommodate high shares of renewables, multiple barriers to their deployment must be addressed by policy makers and regulators. These include: outdated power sector regulatory structures – with marginal pricing failing to provide the right signals for investment in flexibility solutions such as storage options; higher costs compared to incumbent technologies in end-use sectors (*e.g.* heat pumps versus gas boilers or electric vehicles versus internal combustion engine vehicles, or the high and uncertain costs of green hydrogen); and lack of investor confidence due to policy uncertainty.

Policy makers must address these barriers through clear targets and strategies, implemented with specific policies, regulations and incentives. Options include: updating electricity market structures and rules to create an enabling environment for increased system flexibility; policies and incentives to help accelerate end-use electrification; and policies that incentivise indirect electrification, including through green hydrogen.

Targets for grid expansion and storage must be defined based on integrated assessments of national generation mixes and flexibility resources. General guidance ranges from 1 megawatt (MW) to 2 MW of energy storage per 10 MW of renewable power capacity added; but national contexts determine storage needs, as they must be efficiently coupled with generation structures and system capabilities. In a similar way, although reinforcement of grids is an urgent need to avoid bottlenecks in renewable flows, proactive grid expansion must be tailored to national needs. IRENA is ready to support member states from developing countries in assessing their grids, storage and flexibility needs.



Overcoming investment gaps

Renewable energy investments have followed an upward trend but remain concentrated in certain geographies – and regional disparities are on the rise. A global energy transition can only be achieved through a massive scaling up of financing covering multiple countries and regions. Global investments in renewable capacity additions reached USD 570 billion in 2023, compared to USD 448 billion in 2022, representing a 27% increase. Most of the investments were concentrated in China, the United States, Brazil, India and Germany. Indeed, in terms of investment in the energy transition as a whole, half of the world's population – comprising more than 150 economies – received only 10% of investments in 2023. African countries, despite their severe needs and high resource potential, have failed to attract significant financial flows, as investments in least-developed countries are often seen as high risk.

Energy transition investments must increase dramatically to meet the renewable energy and efficiency goals outlined in the First Global Stocktake at COP28. Annual investments in renewable power, grids and flexibility, energy efficiency and conservation must increase from USD 1.29 trillion in 2023 to USD 4.5 trillion each year between 2024 and 2030 to meet the UAE Consensus renewable energy and energy efficiency goals.

Annual investment in the global energy sector as a whole must grow by more than 2.5 times to remain on a 1.5°C pathway. In 2023, the energy sector (including renewables, fossil fuels, grids, energy conservation, electrification, hydrogen, and carbon capture and storage) received USD 2.6 trillion in investments; under the 1.5°C Scenario, cumulative energy sector investment would need to reach USD 47 trillion by 2030, or USD 6.7 trillion, on average, each year between 2024 and 2030 (Figure S2).

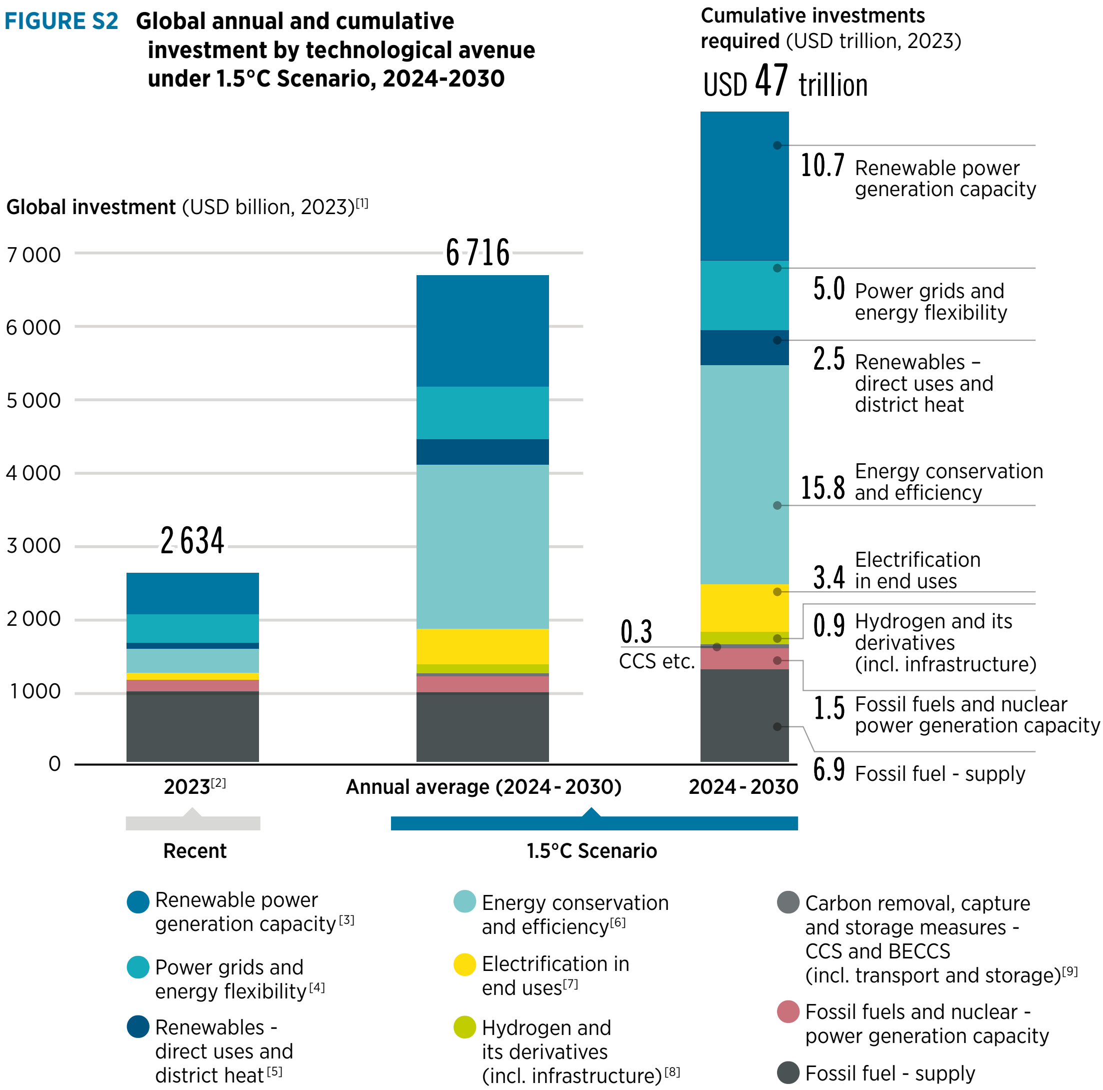
Policies and measures are needed to address prohibitive costs in high-risk environments. Renewable energy investments mainly rely on private capital; the higher the perceived risks, the higher the costs of that capital. As a result, the lowest income populations pay the highest price in meeting their basic energy needs – directly contradicting sustainable development goals such as SDG7. Among the various mechanisms available to policy-makers in collecting revenue to advance a just energy transition, attention is growing concerning the potential of taxation as a means to channel funds to those most in need of energy transition support.

Public financing and policy de-risking must be co-ordinated to shift the focus from bankability to impact potential. Investment decisions should consider factors beyond the immediate financial returns for private investors – including both short- and long-term climate, environmental, socio-economic and development goals – as well as the project's potential to stimulate renewable energy sector growth. More public finance is needed to both de-risk private capital and to channel funds to areas where the private sector is reluctant to engage.

Effective energy planning, backed by robust governance, is needed to establish conditions conducive to private capital investment by reducing risks and transaction costs. This is underscored by the Global Coalition on Energy Planning (GCEP) established under the leadership of the G20 Brazilian presidency, that highlights the critical role of energy planning in accelerating the energy transition.

The New Collective Quantified Goal (NCQG) for climate finance to be agreed at COP29 provides an important opportunity to increase support to the global South. International collaboration will be crucial to better channel funds to a broader range of countries. This will also require larger amounts of public finance, for example to help de-risk projects in high-risk countries and to fund crucial infrastructure. Such funding could, for example, come from a reduction in fossil fuel subsidies.

FIGURE S2 **Global annual and cumulative investment by technological avenue under 1.5°C Scenario, 2024-2030**



Notes: CCS = carbon capture and storage; BECCS = bioenergy with carbon capture and storage

[1] All figures have been adjusted for inflation and are represented in real terms, *i.e.* 2023 US dollars.

[2] (IRENA estimation as of July 2024; BNEF, 2024; WEI, 2023; WEI, 2024; Siepen *et al.*, 2024).

[3] Renewable power generation capacity: Investment in deployment of renewable technologies for power generation.

[4] Power grids and energy flexibility: Investment in transmission and distribution networks (excluding public EV charging stations investments), smart meters, pumped hydropower and battery storage among other energy storage technologies. The average annual investment requirement is based on the lower bound estimates for battery storage capacity of 360 GW.

[5] Renewables direct uses and district heat: Biofuels supply, renewables direct uses and district heat applications (*e.g.* solar thermal, modern bioenergy) and ammonia and methanol production from biomass.

[6] 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. Vehicle stock investments are excluded. Energy efficiency in buildings: Improving building thermal envelopes (insulation, windows, doors, etc.). Energy conservation: Investments in energy conservation includes those in bio-based plastics and organic materials, chemical and mechanical recycling and energy recovery.

[7] Electrification in end uses: Investments in EV charging infrastructure, heat pumps in industry and buildings and transport.

[8] Hydrogen and its derivatives (incl. infrastructure): Electrolyser capacity (alkaline and polymer electrolyte membrane) for the production of green hydrogen, infrastructure for the transport of hydrogen and hydrogen long duration seasonal storage. Hydrogen based ammonia and methanol: Production of ammonia and methanol from hydrogen feedstocks. Historical number is based on spending on projects that entered operation in 2023 (IEA, 2024e).

[9] CCS deployment, mainly for process emissions in industry and blue hydrogen production. BECCS deployment in chemicals, power and cogeneration plants. Historical number is based on spending on projects that entered operation in 2023 (IEA, 2024e).

Ensuring a just and inclusive energy transition

A key benefit of the energy transition is its potential to improve global welfare. As well as positive climate outcomes, the transition can generate co-benefits such as improved economic resilience, jobs, and reliable and affordable access to energy. However, IRENA's analysis of the socio-economic dimensions of the energy transition shows that these benefits cannot be taken for granted. Even if the energy transition follows the 1.5°C Scenario pathway, significant disparities are likely to remain in terms of welfare around the globe.

Inclusive development, equity and justice are key socio-economic dimensions of the energy transition (Figure S3). Inclusive development represents a commitment to globally shared prosperity; equity signifies the fair distribution of the benefits and burdens of the transition; while justice means not leaving anyone behind – for example, those who remain heavily dependent on fossil fuels or lack access to energy.

FIGURE S3 **The socio-economic dimension of the transition with its three pillars (inclusive development, equity and justice) and international collaboration as a transversal element**

Note: The inclusive development component stands for globally shared prosperity, providing space for inclusive development for all. Structural changes in the economy are a key component for opening up space for inclusive development within planetary boundaries (Brand *et al*., 2021; Ensor, and Hoddy, 2021; Richardson *et al*., 2023; Rockstrom *et al*., 2023).

Maximising socio-economic benefits should be a key aim for those planning and implementing the energy transition. The unfolding crises affecting the climate, biodiversity and inequality, only add to the urgency of the energy transition. However, the transition itself could have negative socio-economic and environmental consequences that could intensify biodiversity loss or magnify inequality. Such potential impacts need to be managed through targeted policies and regulations, as well as compensatory measures, where appropriate (*e.g.* financial support for affected communities).

International collaboration is required to secure the significant increase in finance needed for a just and inclusive transition that maximises socio-economic benefits. New sources of finance should be established under guiding principles that emphasise both equity and social or environmental responsibility. These could include, for example, wealth taxation, as in the approach spearheaded by Brazil's G20 Presidency in 2024. A needs-based approach should guide the distribution of collaborative international finance.

The energy access deficit exemplifies the way in which the transition currently leaves many behind. Many of the countries facing the most severe access deficits, such as those in sub-Saharan Africa, have abundant renewable energy resources yet cannot harness their potential to provide affordable energy. Better access to capacity building, affordable finance and existing technologies, would enable these countries to achieve the SDG7 goal of universal energy access and provide opportunities for sustainable economic development.

CHAPTER 01

ACHIEVING THE 1.5°C SCENARIO AND NET-ZERO EMISSIONS BY 2050

KEY POINTS

- Despite efforts to reach carbon reduction targets set through Nationally Determined Contributions (NDCs) and long-term low emission development strategies (LT-LEDS), reductions are projected to be insufficient to keep global average temperatures from rising above 1.5°C of pre-industrial levels by mid-century.
- One response to the predicament is to align NDC updates with national energy strategies, fostering ambition across sectors. In particular, it is important to reflect the global goal to triple renewable power capacity and double energy efficiency improvement rates by 2030 in upcoming climate strategies.
- IRENA's 1.5°C Scenario outlines the path to net-zero emissions by mid-century, with a key focus on renewable energy expansion, energy efficiency and electrification. As the world's largest emitters, the Group of 20 (G20) nations play a crucial role in accelerating decarbonisation efforts.
- Electrification and renewable fuels are key to decarbonising transport, industry and buildings, with renewables in total final energy consumption reaching over 50% by 2050. Clean hydrogen and carbon capture and removal will be essential in sectors where electrification are particularly hard to implement.

01

The year 2024 is likely to represent the warmest on record globally (Abnett and Withers, 2024), and the previous decade (2014-2023) was the warmest since records began in 1850 (NOAA, 2024). Headlines announcing the damage caused by extreme events such as intense flooding and prolonged dry periods are common. As the Intergovernmental Panel on Climate Change has highlighted, anthropogenic greenhouse gas emissions are the major driver behind climate change. Yet, the world just witnessed another record high of global energy-related carbon dioxide (CO_2) emissions – 37.4 gigatonnes (Gt) were released into the atmosphere in 2023 (IEA, 2024a). The chances of achieving the 1.5°C target agreed at the 21st United Nations Climate Change Conference (COP21) in Paris in 2015 are increasingly slim.

Almost ten years on, the required transition of the energy mix from fossil to renewable remains elusive. Most of the G20 nations – the world's largest energy consumers, responsible for more than 80% of global energy consumption – rely on fossil fuels for more than 70% of their primary energy (Figure 1.1). Only Brazil has a lower share, at around 50%. In short, global energy numbers are not yet on a path to net-zero emissions by 2050.

To reverse course, particularly in this decade, will require immediate, rapid action. Pledges made at international fora will not be sufficient. It takes time to turn pledges into concrete, domestic actions – time that the world cannot afford.

1.1 Limited progress in aligning energy and climate plans and strategies

Carbon emissions targets at various levels and time scales have been set in the processes of developing and updating NDCs and LT-LEDS.[1] However, there is a clear gap between these efforts and what is required to actually meet the 1.5°C target. As shown in Figure 1.1, even if all the announcements made in the run-up to the 2023 United Nations Climate Change Conference (COP28) were to be fully implemented, the result would be an additional annual reduction of only 1.4 gigatonnes of carbon dioxide ($GtCO_2$) in 2030 and 2.3 $GtCO_2$ in 2050, beyond the reductions promised in the run-up to the 2022 United Nations Climate Change Conference (COP27). Meanwhile, a gap as large as 18 $GtCO_2$ would still need to be closed by 2050.

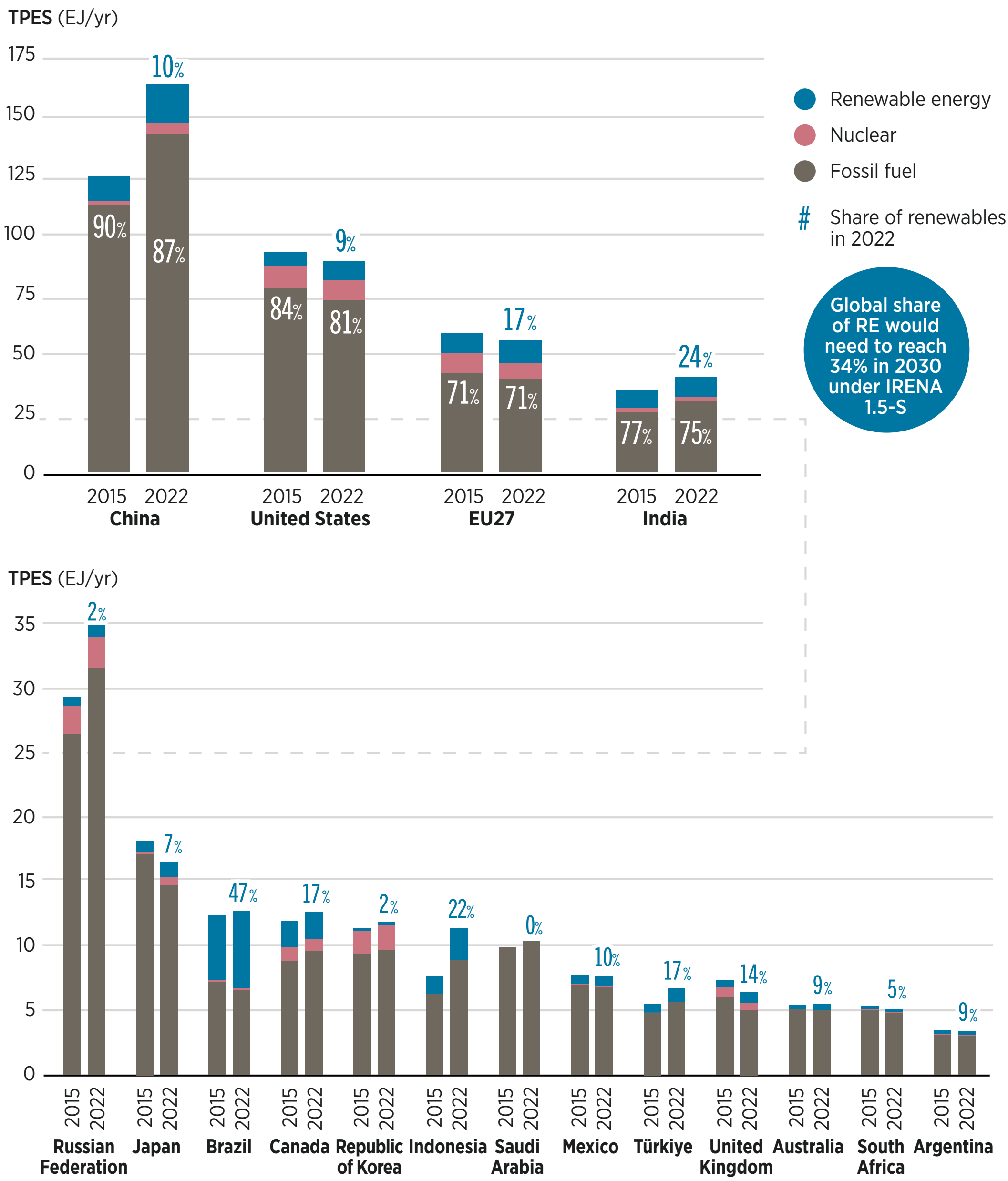
Figure 1.2 estimates global energy-related CO_2 emissions (in gigatonnes) across trajectories that align with 1) the announcements made in the run-up to COP28,[2] 2) the announcements made in the run-up to COP27[3] and 3) IRENA's 1.5°C Scenario (see section 1.2).

1 In accordance with Article 4, paragraph 19, of the Paris Agreement, all Parties should strive to formulate and communicate long-term low greenhouse gas emission development strategies (LT-LEDS) towards just transitions to net-zero emissions by or around mid-century, taking into account different national circumstances.

2 The COP28 announcements' trajectory includes all NDCs, LT-LEDS and net-zero targets communicated by the parties as of 1 December 2023, respectively.

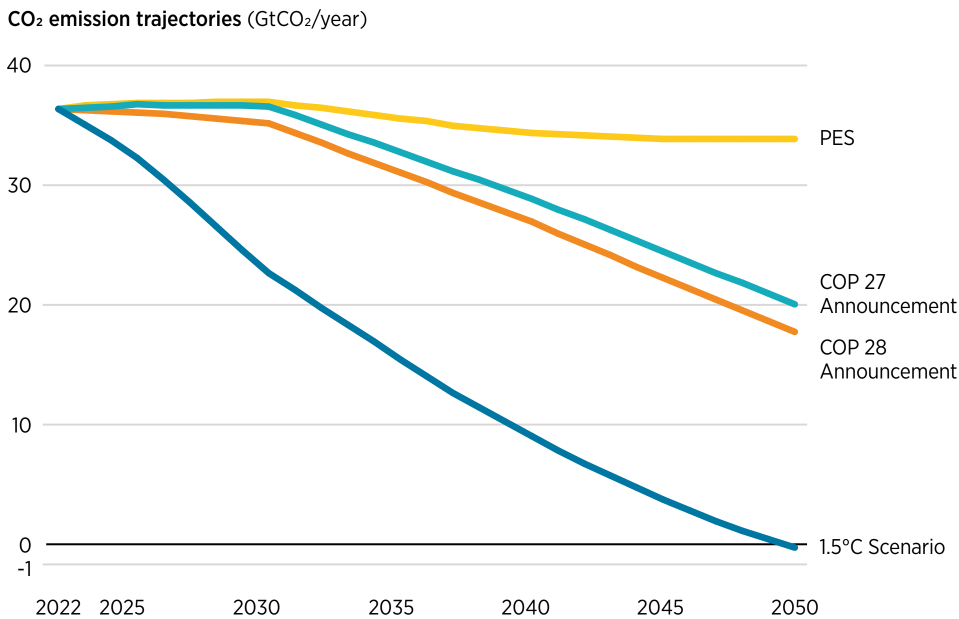
3 The COP27 trajectory includes all NDCs, LT-LEDS and net-zero targets communicated by the parties as of October and November 2022, respectively. Both the COP28 and COP27 trajectories are based on an optimistic climate analysis that assesses the highest ambition (i.e. lowest emission levels) of full NDC implementation, including both conditional and unconditional contributions.

FIGURE 1.1 **Total primary energy supply by energy carrier for G20 nations in 2015 and 2022**



Notes: Historical data from (IEA, 2024b); renewables include hydro, solar, wind, bioenergy, geothermal and marine energy; 1.5C-S = IRENA's 1.5°C Scenario; TPES = total primary energy supply; EJ = exajoule; RE = renewable energy; yr = year.

FIGURE 1.2 **Energy-related CO_2 emission trajectories based on past COP announcements, PES and the 1.5°C Scenario**



Notes: COP announcements trajectory based on data from (Meinshausen *et al.*, 2023); $GtCO_2$ = gigatonne of carbon dioxide; PES = Planned Energy Scenario; COP = conference of the parties (United Nations Climate Change Conference).

Along the COP28 announcements trajectory, global energy-related CO_2 emissions would be 35.2 $GtCO_2$ in 2030. This is significantly more than under the IRENA 1.5°C Scenario, at about 23 $GtCO_2$. Countries' pledges, if fully implemented, could cut global energy-related CO_2 emissions by 3% by 2030 and 51% by 2050, compared with 2022 levels.[4]

To be most effective, NDC updates must be aligned with national energy and climate strategies. NDC update cycles are useful as countries strengthen their LT-LEDS and sectorial action plans, such as for energy. When countries clearly articulate how their short-term actions align with their long-term goals, it becomes easier to track progress, identify challenges and make necessary adjustments. Sector-specific activities and targets can be planned using the framework that coherent, long-term energy and climate strategies have defined, increasing ambition across the economy. Thus, as countries prepare their upcoming NDC update – NDC 3.0 – due in 2025, they are encouraged to align this with their LT-LEDS and net-zero targets, ideally informed by robust modelling and analysis. A coherent national energy and climate strategy can enhance transparency and accountability, attract investment and accelerate the transition to a low-carbon, resilient economy.

LT-LEDS and national energy plans tend to cover similar policy areas when it comes to the energy transition (IRENA, 2023a). In many countries, however, planning processes for energy and climate policies remain separate, potentially leaving stakeholders uncertain about policy direction and the investment decisions that would be influenced by energy plans. A forthcoming report (IRENA, forthcoming) compares LT-LEDS with national energy plans that are based on LTES in over 50 countries, and identifies gaps in alignment with the most ambitious targets of the clean energy transition.

The analysis finds that, in many countries, long-term energy and climate plans are produced by different institutions and use different modelling tools to develop their scenarios, leaving room for the misalignment of their quantitative results. A quarter of the energy plans analysed fail to mention climate plans in their text, and *vice versa*.

LT-LEDS generally tend to be more ambitious than energy planning documents towards 2050. Notably, in two-thirds of the countries considered, the LT-LEDS were published before the national energy plan, suggesting that even more recent energy plans are not as ambitious as older LT-LEDS. If ambitious climate targets are not backed by results from the national energy planning process, this could hinder the implementation of climate plans.

To bridge this co-ordination gap in planning and strategy development, the *World Energy Transitions Outlook* provides an overarching long-term framework. In particular, tripling global installed renewable power generation capacity by 2030, as part of IRENA's 1.5°C Scenario, should be reflected to a greater extent in climate strategies, NDC updates and LT-LEDS.

4 The COP27 announcements' and COP28 announcements' trajectories presented in this report exclude CO_2 emissions from agriculture, forestry and other land uses (AFOLU). The 2023 version of this report showed the COP27 announcements trajectory with a different scope – including AFOLU CO_2 emissions. This is why the trajectory in the 2023 Outlook presents lower CO_2 emissions and why the relative CO_2 emissions reductions in the COP28 announcements trajectory do not increase compared to the emissions trajectory showed in the last report.

1.2 IRENA's 1.5°C Scenario: A framework for aligning energy and climate strategies and tracking plans

The *World Energy Transitions Outlook* offers a framework for developing energy transition strategies and tracking progress towards net-zero emissions by mid-century.

The Outlook framework uses six key performance indicators (KPIs) to help policy makers identify priority actions, assess progress and guide strategic actions towards the 1.5°C climate goal at a global scale.

First, the use of renewables to generate electricity is monitored through two sub-indicators: 1) the amount of electricity generated from renewables and 2) the share of renewables in the total electricity generated. This indicator highlights the importance of increasing renewable energy capacity and its contribution to the overall energy mix.

Second, the direct use of renewables is assessed by looking at the share of renewable energy in total final energy consumption and the quantity of modern bioenergy used. It is necessary to integrate renewables across various sectors and increase the use of sustainable bioenergy.

Energy intensity improvement rates are a proxy for energy efficiency improvement rates. Energy intensity is calculated as total primary energy supply (TPES) divided by gross domestic product (GDP); energy intensity improvement is the compound rate at which energy intensity declines annually at the global level. Improvements in energy intensity are tracked to measure the efficiency gains in energy use, crucial for reducing overall energy demand and emissions.

The electrification of end-use sectors is another key indicator, as it reflects the shift towards electricity as a key energy carrier, essential for decarbonising sectors like transport and heating and energy efficiency improvement.

The production and supply of green hydrogen and its derivative fuels are also monitored. As versatile, carbon-free energy sources, these play a central role in the energy transition.

Finally, the framework tracks the amount of CO_2 captured and removed by various measures, underscoring the importance of carbon capture and carbon removal technologies in achieving net-zero emissions.

Table 1.1 introduces the KPIs that underpin the *World Energy Transitions Outlook* framework, comparing the 1.5°C Scenario with the Planned Energy Scenario for 2030 and 2050. It provides a snapshot of the progress required across sectors to meet the 1.5°C climate target.

TABLE 1.1 Key performance indicators for achieving the 1.5°C Scenario compared with the Planned Energy Scenario in 2030 and 2050: Global perspective

GLOBAL PERSPECTIVE	Historical			Planned Energy Scenario (PES)[1]		1.5°C Scenario[1]		Essential milestones
	2021	2022	2023	2030	2050	2030	2050	
KPI.01 RENEWABLES (POWER)[2]								
Renewable energy electricity generation (TWh/yr)	7 873	8 440	N/A	16 504	38 118	27 358	82 148	• Tripling renewable capacity by 2030. • Nine-fold increase in renewables by 2050. • Renewable electricity share in electricity generation to reach c. 70% by 2030 and 90% by 2050.
Renewable energy share in electricity generation (%)	28	29	N/A	46	73	68	91	
Renewable energy installed capacity (GW)	3 083	3 391	3 865	6 773	15 835	11 174	33 216	
Renewable energy share in installed capacity (%)	38	40	43	58	80	77	94	
KPI.02 RENEWABLES (DIRECT USES)								
Renewable energy share in TFEC (%)	17[3]	17[3]	N/A	23	33	35	78	• Doubling the direct use of renewable energy by 2030 and quadrupling it by 2050. • Tripling modern use of bioenergy by 2050.
Modern use of bioenergy (EJ)[4]	23[3]	24[3]	N/A	30	41	46	53	
KPI.03 ENERGY INTENSITY								
Energy intensity improvement rate (%)	0.7[5]	2[5]	N/A	2[6]	2[7]	4[6]	3[7]	• Urgent doubling energy efficiency improvements by 2030.

TABLE 1.1 Key performance indicators for achieving the 1.5°C Scenario compared with the Planned Energy Scenario in 2030 and 2050: Global perspective (continued)

GLOBAL PERSPECTIVE	Historical			Planned Energy Scenario (PES)[1]		1.5°C Scenario[1]		Essential milestones
	2021	2022	2023	2030	2050	2030	2050	
KPI.04 ELECTRIFICATION IN END-USE SECTORS (DIRECT)								
Electrification rate in TFEC (%)	22[3]	23[3]	N/A	23	28	30	52	• Direct electrification of end-use sectors would need to increase by 50% by 2030 and more than double by 2050.
KPI.05 CLEAN HYDROGEN AND DERIVATIVES								
Production of clean hydrogen (Mt)	0.6[8]	0.7[8]	0.7[8]	2	21	125	523	• A new set of hydrogen facilities to be scaled up by 2030 and beyond.
KPI.06 CCS, BECCS AND OTHERS								
CO_2 captured from CCS, BECCS and other removal measures (Gt)	0.05[9]	0.05[9]	0.05[9]	0.1	0.5	2.2	7.0	• CO_2 removal, capture and storage measures also needed – to 2.2 Gt and 7 Gt by 2030 and 2050.

Notes: The scenario results presented herein are subject to upward revision in the 2025 edition of the *World Energy Transitions Outlook*, given the current pace of solar and storage growth in certain countries.
BECCS = bioenergy with carbon capture and storage; CCS = carbon capture and storage; CO_2 = carbon dioxide; EJ = exajoule; GW = gigawatt; Gt= gigatonne; KPI = key performance indicator; Mt = megatonne; PES = Planned Energy Scenario; TFEC = total final energy consumption; TWh/yr = terawatt hour per year.

[1] PES and 1.5°C Scenario analyses as of March 2023.
[2] (IRENA, 2024a).
[3] Based on (IEA, 2024b).
[4] Excludes non-energy uses.
[5] Energy intensity improvement achieved estimated using (IEA, 2024b) for primary energy supply and (CE, *n.d.*) for GDP statistics.
[6] Average annual improvement rate from 2023 to 2030 uses (IEA, 2024b) for primary energy supply (historical data), and (CE, *n.d.*) for GDP historical statistics.
[7] Average annual improvement rate from 2023 to 2050 uses (IEA, 2024b) for primary energy supply (historical data), and (CE, *n.d.*) for GDP historical statistics.
[8] (IEA, 2023a).
[9] (IEA, 2024c).

Expanded renewable power generation capacity in all countries will be required to meet the 1.5°C target. G20 nations' efforts to double global energy efficiency are also essential, since these countries account for more than 70% of global final energy demand (IEA, 2024b). The G20 nations will account for most of the globe's installed renewable capacity: 84% in 2030 and 75% in 2050. Aligning with the 1.5°C pathway would require G20 nations' renewable capacity to almost triple by 2030 (approximately 9 400 GW) and scale up by more than seven-fold by 2050 (approximately 24 900 GW), relative to 2023.

Electrification not only supports the decarbonisation of end-use sectors but also reduces energy consumption in those sectors. Considering that more than 80% of global electricity is consumed in G20 nations (IEA, 2024b), electrification will play a key role in achieving the global energy efficiency target. Under IRENA's 1.5°C Scenario, G20 nations would need to meet 32% of their final energy consumption through direct electrification, up from 25% in 2022.

Beyond direct electrification and energy efficiency, G20 nations will also need to lead the deployment of innovative technologies such as clean hydrogen and its derivatives and carbon capture to achieve global net-zero emissions by 2050. Under the 1.5°C Scenario, the use of clean hydrogen would increase from current negligible levels to more than 3% and 14% of total final energy consumption (TFEC) by 2030 and 2050, respectively. G20 nations would produce and consume more than 75% of global hydrogen supply by 2030. Furthermore, more than 95% of CO_2 emissions would be captured in G20 nations by 2030. The G20 nations' share of global hydrogen supply and use as well as carbon capture would decline slightly by 2050 as other countries follow their example.

The 1.5°C Scenario envisions a transition driven by the deployment of renewable energy, improvements in energy efficiency and the electrification of end-use sectors. Electricity becomes the main energy carrier by 2050 owing to its cost competitiveness and scalability. The shift would result in electricity accounting for over 50% of TFEC by 2050, a substantial increase from 2022 levels (see Figure 1.3). Alongside direct electrification, clean hydrogen and its derivatives would also play an important role in decarbonising the industrial and transport sectors, where electrification is particularly hard to implement. In the industry sector, clean hydrogen can substitute for fossil-fuel-based feedstocks in the production of iron, steel and chemicals. In heavy-duty transport, clean hydrogen and its derivatives can be used as fuel for long-haul aviation and shipping.

TABLE 1.2 **Key performance indicators for achieving the 1.5°C Scenario compared with the Planned Energy Scenario in 2030 and 2050: G20 perspectives**

KPI.01 RENEWABLES (POWER)[2]

G20 PERSPECTIVES	Historical			Planned Energy Scenario (PES)[1]		1.5°C Scenario[1]		Essential milestones
	2021	2022	2023	2030	2050	2030	2050	
Renewable energy electricity generation (TWh/yr)	6 556	7 081	N/A	14 269	31 071	22 397	60 547	• G20 nations together would account for the c. 84% and 75% of the global installed renewable capacity by 2030 and 2050 respectively. • Tripling renewable capacity by 2030. • Seven-fold increase of renewable capacity by 2050. • Renewable electricity share in electricity generation to reach c. 70% by 2030 and 90% by 2050.
Renewable energy share in electricity generation (%)	27	29	N/A	48	74	69	91	
Renewable energy installed capacity (GW)	2 684	2 968	3 418	5 959	13 144	9 359	24 868	
Renewable energy share in installed capacity (%)	39	42	45	62	84	80	95	

KPI.02 RENEWABLES (DIRECT USES)

G20 PERSPECTIVES	Historical			Planned Energy Scenario (PES)[1]		1.5°C Scenario[1]		Essential milestones
	2021	2022	2023	2030	2050	2030	2050	
Renewable energy share in TFEC (%)	15[3]	15[3]	N/A	22	35	36	82	• Doubling the direct use of renewable energy by 2030 and more than quadrupling it by 2050. • Modern use of bioenergy to reach 33 EJ by 2030.
Modern use of bioenergy (EJ)[4]	19[3]	20[3]	N/A	26	33	33	34	

KPI.03 ENERGY INTENSITY

G20 PERSPECTIVES	Historical			Planned Energy Scenario (PES)[1]		1.5°C Scenario[1]		Essential milestones
	2021	2022	2023	2030	2050	2030	2050	
Energy intensity improvement rate (%)	0.4[5]	2[5]	N/A	2[6]	2[7]	4[6]	3[7]	• Urgent doubling energy efficiency improvements by 2030.

TABLE 1.2 Key performance indicators for achieving the 1.5°C Scenario compared with the Planned Energy Scenario in 2030 and 2050: G20 perspectives (continued)

G20 PERSPECTIVES	Historical			Planned Energy Scenario (PES)[1]		1.5°C Scenario[1]		G20
	2021	2022	2023	2030	2050	2030	2050	Essential milestones
KPI.04 ELECTRIFICATION IN END-USE SECTORS (DIRECT)								
Electrification rate in TFEC (%)	24[3]	25[3]	N/A	26	32	32	55	• Direct electrification of end-use sectors would need to increase by roughly 30% by 2030, from its current 25% and more than double by 2050.
KPI.05 CLEAN HYDROGEN AND DERIVATIVES								
Production of clean hydrogen (Mt)	0.6[8]	0.7[8]	0.7[8]	2	20	94	373	• G20 nations would need to increase clean hydrogen demand and produce 75% of global demand by 2030.
KPI.06 CCS, BECCS AND OTHERS								
CO_2 captured from CCS, BECCS and other removal measures (Gt)	0.05[9]	0.05[9]	0.05[9]	0.1	0.4	2.1	4.9	• 95% of CO_2 to be captured by 2030 would need to be covered by G20 nations.

Notes: BECCS = bioenergy with carbon capture and storage; CCS = carbon capture and storage; CO_2 = carbon dioxide; EJ = exajoule; GW = gigawatt; Gt= gigatonne; KPI = key performance indicator; Mt = megatonne; PES = Planned Energy Scenario; TFEC = total final energy consumption; TWh/yr = terawatt hour per year.

[1] PES and 1.5°C analyses are as of March 2023.

[2] (IRENA, 2024a).

[3] Based on (IEA, 2024b).

[4] Excludes non-energy uses.

[5] Energy intensity improvement achieved over the year estimated using (IEA, 2024b) for primary energy supply and (CE, n.d.) for GDP statistics.

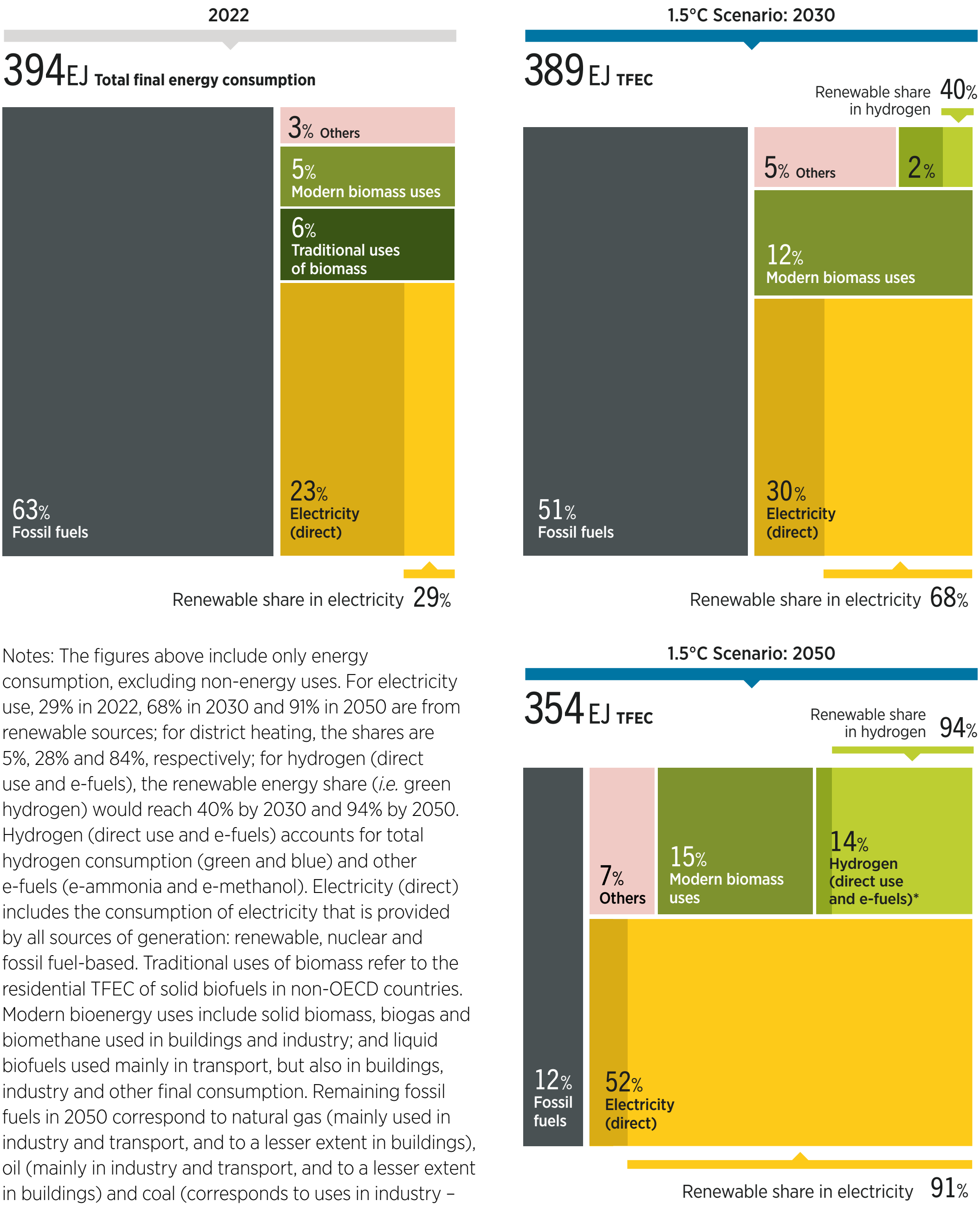
[6] Average annual improvement rate from 2023 to 2030 uses (IEA, 2024b) for primary energy supply (historical data), and (CE, n.d.) for GDP historical statistics.

[7] Average annual improvement rate from 2023 to 2050 uses (IEA, 2024b) for primary energy supply (historical data), and (CE, n.d.) for GDP historical statistics.

[8] (IEA, 2023a).

[9] (IEA, 2024c).

FIGURE 1.3 **Breakdown of total final energy consumption by energy carrier between 2022, 2030 and 2050 under the 1 .5°C Scenario**

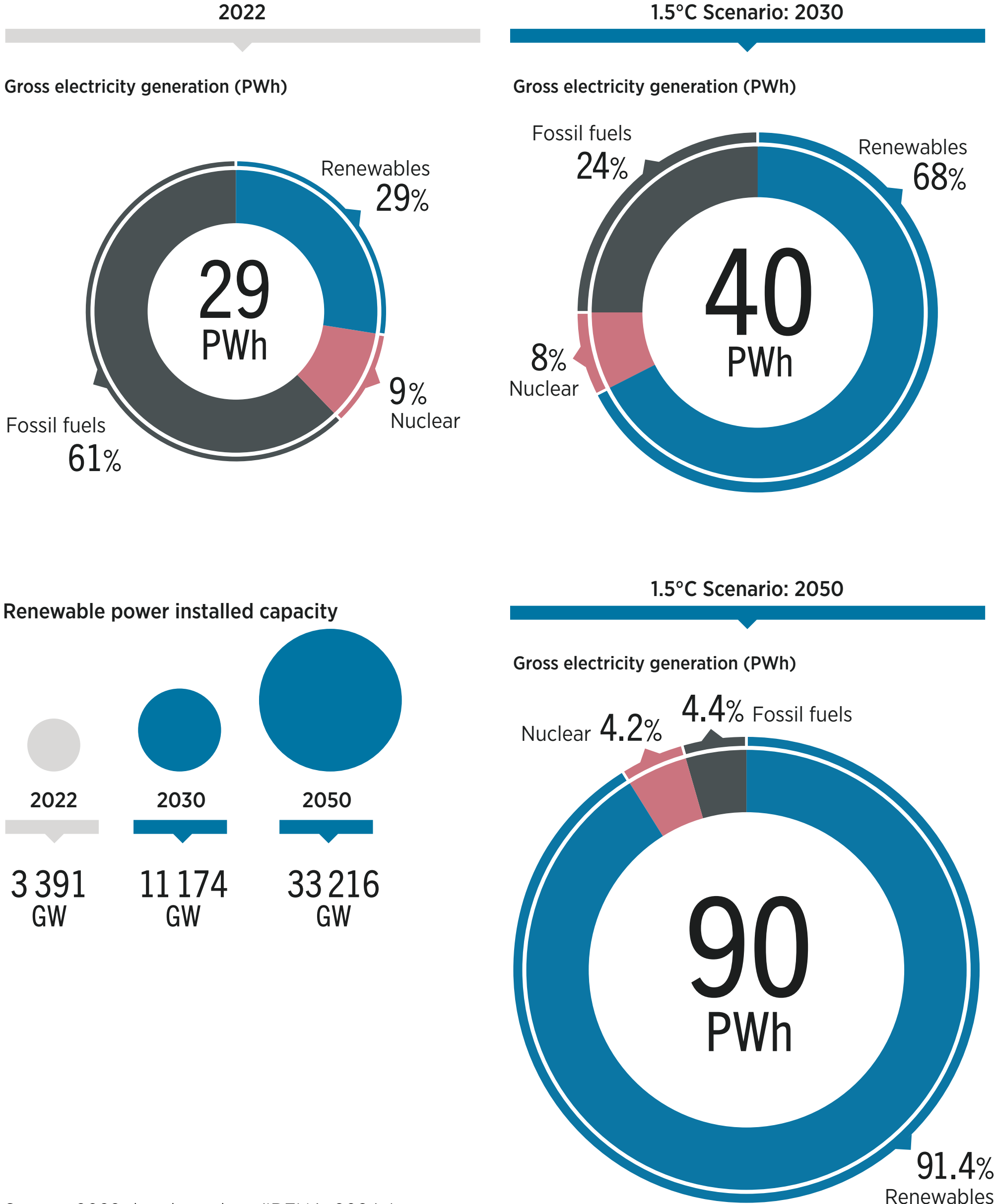


Notes: The figures above include only energy consumption, excluding non-energy uses. For electricity use, 29% in 2022, 68% in 2030 and 91% in 2050 are from renewable sources; for district heating, the shares are 5%, 28% and 84%, respectively; for hydrogen (direct use and e-fuels), the renewable energy share (*i.e.* green hydrogen) would reach 40% by 2030 and 94% by 2050. 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 the consumption of electricity that is provided by all sources of generation: renewable, nuclear and fossil fuel-based. Traditional uses of biomass refer to the residential TFEC of solid biofuels in non-OECD countries. Modern bioenergy uses include solid biomass, biogas and biomethane used in buildings and industry; and liquid biofuels used mainly in transport, but also in buildings, industry and other final consumption. Remaining fossil fuels in 2050 correspond to natural gas (mainly used in industry and transport, and to a lesser extent in buildings), oil (mainly in industry and transport, and to a lesser extent in buildings) and coal (corresponds to uses in industry – cement, chemicals, iron and steel). Others include district heat and other renewables consumption.
EJ = exajoule; OECD = Organisation for Economic Co-operation and Development; TFEC = total final energy consumption.

Important as it is, electrification is not a complete solution to decarbonisation, nor even the most efficient one. Direct use of renewables – including bioenergy, solar thermal and geothermal – may offer a better option in some cases. Modern use of bioenergy is expected to play a growing role, accounting for 12% and 15% of TFEC by 2030 and 2050, respectively. Overall, the share of renewable energy in TFEC would increase from 17% in 2022 to 68% by 2030 and further to 82% by 2050 under the 1.5°C Scenario. Thanks to improvements in energy efficiency, in part due to electrification, TFEC would fall by 8% between 2022 and 2050.

Under the 1.5°C Scenario, electricity generation would have to expand from 29 petawatt hours (PWh) in 2022 to approximately 40 PWh by 2030 and 90 PWh by 2050. Renewable energy sources would provide the bulk of the power mix, accounting for 68% and 91% of the total electricity supply by 2030 and 2050, respectively – a significant rise from the 29% observed in 2022 (see Figure 1.4). This expansion of renewable electricity will facilitate the transition away from fossil fuels in the power sector. The share of fossil fuels will significantly shrink from a dominant share of 61% in the global power generation mix in 2022, to 24% by the end of this decade and further to 4.4% by 2050. Nuclear power plants are expected to provide 8% of total electricity needs by 2030 and around 4% by 2050.

FIGURE 1.4 Scaling power generation needs under the 1.5°C Scenario by 2030 and 2050, compared to 2022 progress

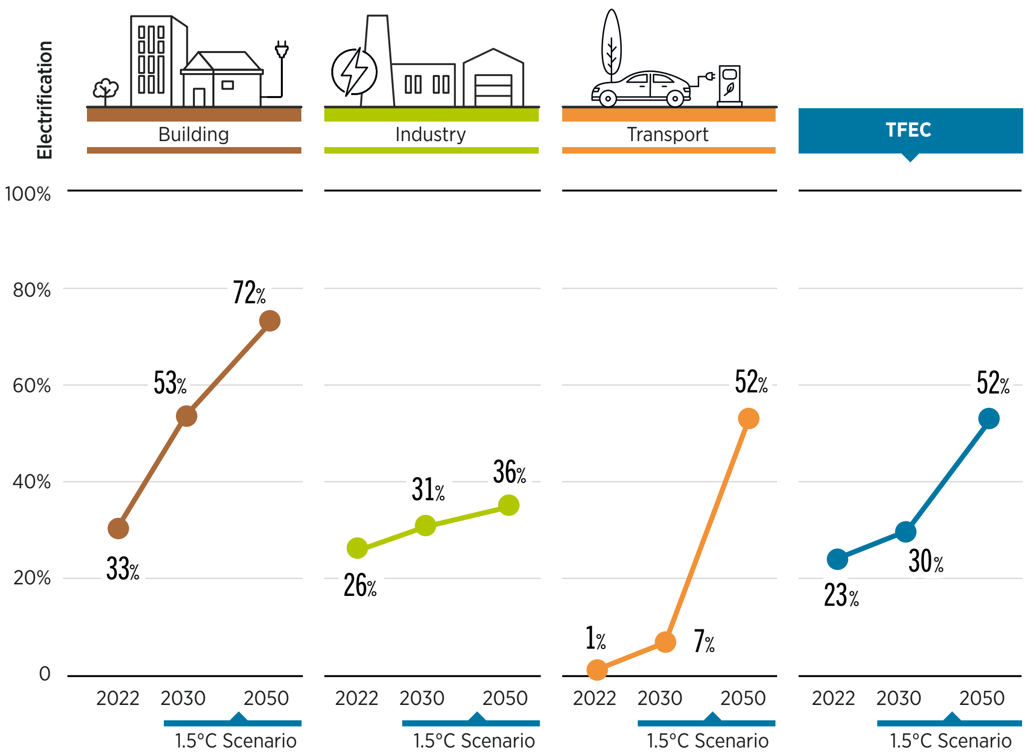


Source: 2022 data based on (IRENA, 2024a),
Notes: GW = gigawatt; PWh = petawatt hours.

This transformation is accompanied by the wider adoption of electric vehicles (EVs), energy-efficient technologies in industries and buildings powered by renewable energy technologies. The electrification of the end-use sector implies that global renewable power generation capacity would need to triple by 2030 and expand by a factor of 9 by 2050, compared to 2022 levels, to meet the 1.5°C target.

In 2022, the share of electricity consumption in the buildings, industry and transport sectors' final energy consumption, was 33%, 26% and 1.3%, respectively (IEA, 2024b). To keep up with decarbonisation targets, significant increases in the electrification rates across these sectors are necessary. By 2030, the electrification rate in the buildings sector is expected to reach 53%, the industry sector 31%, while the transport sector is projected to rise to 7%. And looking further ahead to 2050, the buildings and transport sectors will need to take an even bigger leap forward, achieving electrification rates of 72% and 52%, respectively. The industry sector's electrification rate will need to rise to 36% by 2050 (see Figure 1.5).

FIGURE 1.5 Global electrification in end-use sectors and TFEC, 2022, 2030 and 2050 under the 1.5°C Scenario



Source: Historical data from (IEA, 2024b)

Note: TFEC = total final energy consumption

Achieving these electrification targets will require widespread adoption of advanced technologies across the buildings, industry and transport sectors. The different end-use sectors are associated with a diverse range of electrification technologies, each at varying levels of deployment. Their uptake is influenced by continued technological innovation, emission reduction policies, energy prices and market readiness across the supply chain. In buildings, technologies like heat pumps will play a crucial role in reducing reliance on fossil fuels; it is envisioned that their use will grow twelve-fold by 2050 in the 1.5°C Scenario. The transport sector will need to see further deployment of EVs, supported by a robust charging infrastructure, advancements in battery technology, and electrification in shipping, rail and public transport. IRENA's 1.5°C Scenario estimates that the global stock of electric and plug-in hybrid light passenger vehicles would need to grow 50 times to more than 2 billion EVs in 2050.

Large-scale heat pumps, used in district networks and to supply heat to buildings and industry, are as mature as their residential counterparts. A total installed capacity of 2.5 gigawatt thermal is found in the 27 member countries of the European Union (EU-27), representing around 1% of Europe's district heating and cooling capacity (Euroheat & Power, 2022). China, the Russian Federation and the EU-27 produce close to 90% of global district heat (Werner, 2017), and thus have an outsize role to play in its decarbonisation. In the 1.5°C Scenario, large-scale heat pumps would consume about 0.5 EJ of final energy for district heating in 2030 and up to 3 EJ in 2050.

Relative to space heating, industrial processes have a different and often unique set of requirements in increasingly diverse end-use applications, ranging from low-temperature heat for drying to high-temperature process steam (IRENA, 2022b). In the 1.5°C Scenario, large-scale heat pumps would consume about 2.6 EJ of the final energy to meet heat demand for industrial processes in 2030, and just below 4 EJ in 2050.

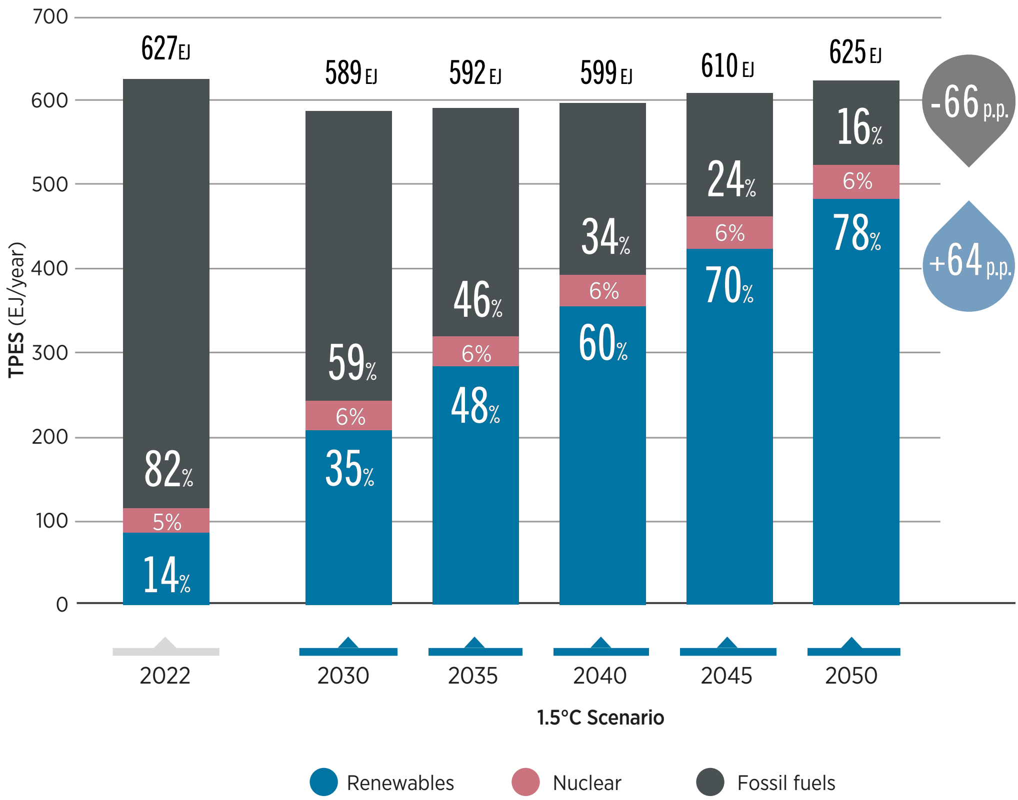
Besides the direct electrification of end-use sectors, the 1.5°C Scenario foresees a substantial expansion of electrolysers to produce green hydrogen as part of the indirect electrification process. Low-emission hydrogen demand would grow from negligible levels today to almost 125 million tonnes (Mt) by 2030, rising to 523 Mt by 2050. Around 40% would be produced via electrolysis using renewable electricity in 2030. This share would increase up to 94% by 2050. Hydrogen and its derivative fuels – ammonia, methanol and kerosene – would account for 16% of total final consumption in 2050 (including consumption for purposes other than energy). Early investment in the green hydrogen supply chain (electrolysis, fuel cells, transport pipelines, storage caverns, etc.) is vital to the uptake of hydrogen applications in end-use sectors and to carbon reduction goals. This is especially the case for hard-to-decarbonise sectors like aviation, marine and heavy-duty transport, as well as some primary industrial processes.

The electricity needed for green hydrogen production would amount to approximately 6% and 28% of global power generation in 2030 and 2050, respectively. This implies that cumulative installed electrolyser capacity would need to grow 162-fold from 2.9 GW in 2023 (IEA, 2023b), reaching around 470 GW by 2030 and then expanding to reach 5 470 GW by 2050. Globally, electrolyser manufacturing capacity had reached 31.7 GW per year by the end of 2023 and manufacturers announced further expansion of capacity to exceed 50 GW by the end of 2024 (Martin, 2024), and more than 130 GW per year by 2030 (IEA, 2023b). The integrated planning and development of a full supply chain and manufacturing capacity are needed in the 1.5°C Scenario.

In summary, the share of renewable energy in primary energy supply would grow from 14% in 2022 (IEA, 2024b) to 77% in 2050 (see Figure 1.6). The energy mix would change drastically in the process, with a net gain of 61 percentage points of renewable energy share in TPES, driven by a mix of end-use electrification, renewable fuels and direct uses. Achieving this level of renewable energy is critical to meeting global climate goals and would require significant investment and policy support, as well as continued innovation. In 2022, the global energy mix was dominated by fossil fuels, contributing 82% of TPES, while renewables and nuclear accounted for 14% and 5%, respectively.

Lastly, although ambitious expansions of renewables and efficiency measures account for most emission reductions, remaining CO_2 emissions from fossil fuels – primarily in industrial processes and power generation – would require carbon capture and storage technologies together with CO_2 removal measures. With only 0.05 Gt of carbon captured in 2023, removal and storage measures – from CCS to bioenergy with carbon capture and storage (BECCUS), and other methods – will have to be scaled up to make the 1.5°C Scenario a reality. Captured carbon emissions would have to reach 2.2 Gt by 2030, and 7 Gt by 2050.

FIGURE 1.6 Total primary energy supply by energy carrier group, 2022–2050 under the 1.5°C Scenario



Notes: Global primary energy supply refers to the total amount of energy that is produced and consumed in various forms around the world. It includes all the energy sources that are used to produce electricity, power transportation, heat buildings and homes, and power industrial processes. Renewables include hydro, solar, wind, bioenergy, geothermal and ocean energy. EJ/yr = exajoules per year; p.p. = percentage points; TPES = total primary energy supply.

CHAPTER 02

PROGRESS TOWARDS **2030 MILESTONES**

KEY POINTS

- Global renewable power generation capacity reached 43% of total power, with a record 473 GW added in 2023. Geographically, the growth was concentrated in China, the European Union and the United States representing 83% of the 2023 additions. Further expanding renewables in other regions and countries, particularly in developing countries, is critical to meet growing energy demand and global decarbonisation targets.
- Tripling global renewable power capacity by 2030 is a feasible target, but it requires a massive annual addition of 1044 GW, nearly double the 2023 rate. While solar PV is on track, lagging technologies like wind and bioenergy require urgent policy support and investment, especially in emerging markets.
- Achieving the tripling target calls for a holistic approach, including the rapid scaling of all renewable technologies, enhanced infrastructure, supply chain improvements and significant investment, while fossil fuel capacity needs to be reduced.
- Energy transition investments must increase dramatically to meet the renewable energy and efficiency goals outlined in the First Global Stocktake at COP28. Annual investments in renewable power, grids and flexibility, energy efficiency and conservation must increase from USD 1.29 trillion in 2023 to USD 4.5 trillion each year between 2024 and 2030 to meet the UAE Consensus renewable energy and energy efficiency goals.
- As part of the UAE Consensus, agreed at the 28th United Nations Climate Change Conference in Dubai, energy efficiency improvement must double by 2030 through advanced technologies, structural changes and behavioural shifts across all sectors. Pairing electrification with energy efficiency cuts carbon emissions, as technologies such as heat pumps and electric vehicles boost renewable energy use and energy efficiency improvements.

02

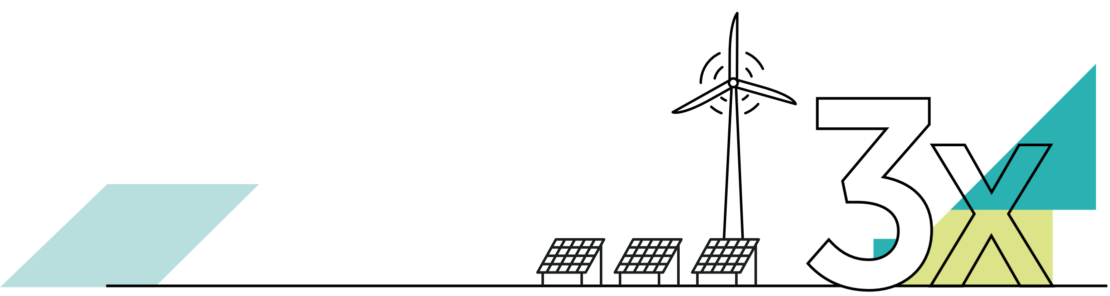
Without losing sight of the path towards net-zero emissions by 2050, implementation efforts should focus on the 2030 milestones. The priorities are to triple renewable energy capacity by 2030 and double energy efficiency improvement rates as part of a global effort to expand renewables-based electrification thereby reducing the global demand for fossil fuels, while at the same time minimising the overall growth of energy demand.

If the world can achieve the 2030 targets, the global energy transition could be brought back on track to deliver net-zero emissions by 2050. IRENA urges all parties to engage across sectors, speed up the deployment of renewables and implement carbon mitigation measures to keep the 1.5°C climate target alive.

The IRENA 1.5°C Scenario directly informed part of the Outcome of the First Global Stocktake (known as the UAE Consensus) agreed at the 28th United Nations Climate Change Conference (COP28) in 2023. The Consensus calls on all parties to the UNFCCC to triple renewable energy capacity and double the rate of energy efficiency improvement by 2030 (UNFCCC, 2023). Also at COP28, as part of the Global Renewables and Energy Efficiency Pledge, more than 130 parties explicitly committed to work together to *"triple the world's installed renewable energy generation capacity to at least 11 000 GW by 2030 . . ."*, and *"to collectively double the global average annual rate of energy efficiency improvements from around 2% to over 4% every year until 2030"* (COP28, 2023[1]). These followed pledges made at the G20 Summit in September 2023, where leaders agreed to triple total renewable energy capacity by 2030 and underscored the global need for annual investments of more than USD 4 trillion through 2030.

Tripling global renewable power capacity must be coupled with end-use electrification, physical and digital infrastructure enhancement and modernisation and a skilled workforce. These will rest on cross-sector policy and regulation alignment, scaled up financing and more international collaboration.

Despite progress, the energy transition is off track, and only radical action can change the trajectory. In early 2024, the COP28 Presidency appointed IRENA the custodian agency for tracking progress on the renewable energy and energy efficiency milestones set out in section 28(a) of the UAE Consensus. Under the Presidency of the Republic of Azerbaijan, the 29th United Nations Climate Change Conference (COP29) provides another opportunity in 2024 to bring the world back on track to deliver a just and equitable energy transition, in line with the goals of the Paris Agreement. This includes the adoption of a New Collective Quantified Goal for climate finance to support developing countries in tackling the climate crisis (IRENA *et al.*, 2024).



1 www.cop28.com/en/global-renewables-and-energy-efficiency-pledge.

2.1 Progress in renewable power capacity development

2.1.1 Current status

The year 2023 witnessed record growth in renewable power capacity additions, at 473 GW, representing 86% of the power capacity that was added in the year. Growth was driven by supportive industrial policies, incentives, regulatory and market frameworks, technological advancement and the associated increase in cost-effectiveness, and energy security and environmental concerns. Currently, renewables account for 43% of the global total power generation capacity.

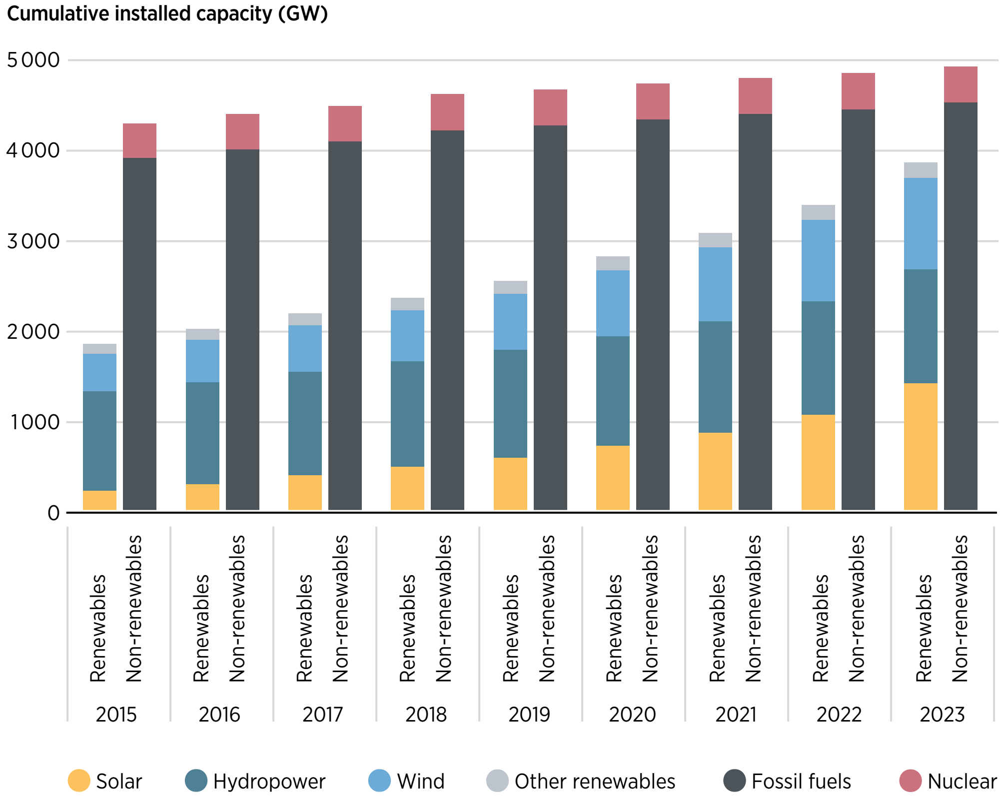
The shift towards renewable energy is spearheaded by solar PV, which accounted for nearly three-quarters (73%) of renewable capacity growth in 2023. By the year's end, global installed capacity of solar PV stood at 1411 GW, of which 347 GW was added in 2023 alone, 73% more than the previous record 200 GW set in 2022. China accounted for 63% of global solar PV capacity additions, followed by the European Union (15%) and the United States (7%). The solar PV capacity added in 2023 almost equals all such capacity added in the eight years from 2010 to 2017.

Also in 2023, global installed wind capacity reached 1017 GW, around half of it in Asia. Capacity additions reached 114.5 GW, a new record. Additions of onshore wind capacity, at 103.9 GW, matched the record set in 2020. Offshore wind capacity increased by 11 GW, a modest gain that reflects the limited projects outside China, higher material costs, permitting delays, policy uncertainty and supply chain disruption.

Global hydropower installed capacity (excluding pumped hydro) reached 1265 GW in 2023, or 33% of total renewable capacity. Net capacity additions that year (6.6 GW) were modest compared to the additions of the preceding seven years. Large-scale hydropower development has decelerated in China, Latin America and Europe; most viable locations have been developed, while other projects face permitting or financing delays.

At the end of 2023 other renewable power generation technologies (bioenergy, geothermal, concentrated solar power [CSP] and marine energy) saw their combined installed capacity reach 171 GW (with 5.2 GW added in 2023); bioenergy accounted for 87%. Figure 2.1 illustrates cumulative growth in power capacity for 2015-2023, while Figure 2.2 disaggregates annual additions.

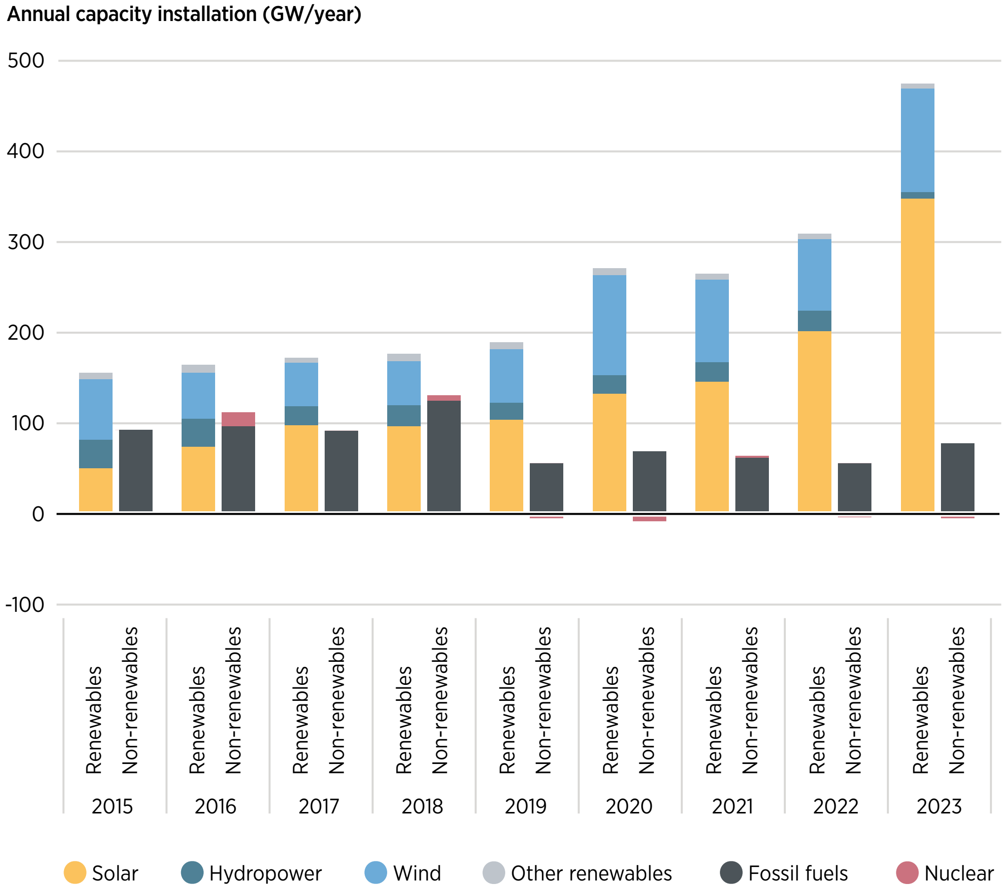
FIGURE 2.1 **Global power capacity by technology, 2015-2023**



Source: (IRENA, 2024a).
Notes: GW = gigawatt; hydropower data excludes pumped hydro.

Global aggregates mask persistent patterns of geographical concentration. Overall, deployment is greatest in China, the European Union and the United States, as shown in Figure 2.3. Collectively, these three front runners accounted for approximately 85% of new capacity additions in 2023 (IRENA, 2024a). China reached a new milestone in 2023, with 85% of its new capacity originating from renewables. This development is spurred by the decreasing cost of utility-scale solar and wind power, supportive energy and industrial policies. Wind and solar overtook fossil fuels in the first half of 2024 for power generation in the European Union, indicating the shrinking role of fossil fuels in the contexts of the accelerating energy transition and the growing concerns over security of fossil fuel supply (Graham and Fulghum, 2024). To meet the targets of the 1.5°C Scenario, the adoption of renewable technology should be accelerated in regions and countries beyond the three front runners. Although renewable energy is typically deployed at various scales in countries with well-developed power systems, the focus should shift to areas of emerging and developing nations that currently lacking electricity access and are poised to drive future electricity demand.

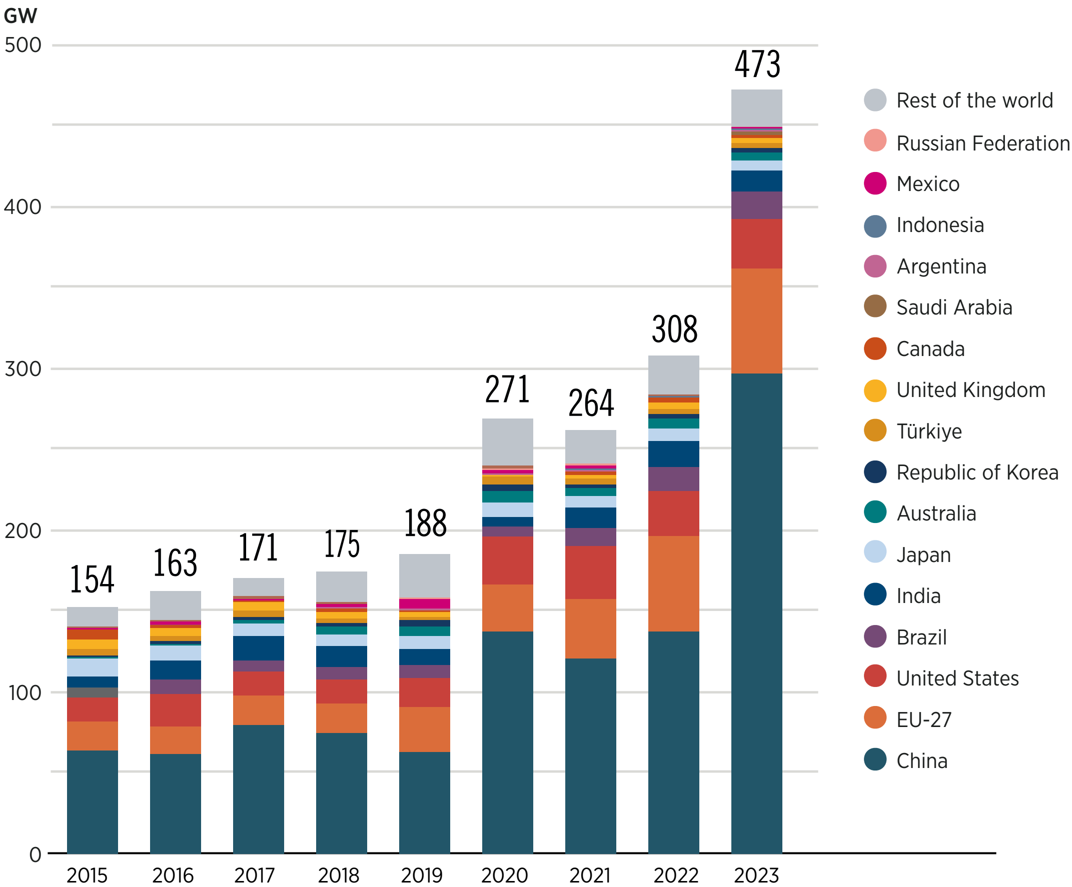
FIGURE 2.2 Global annual power capacity additions by technology, 2015–2023



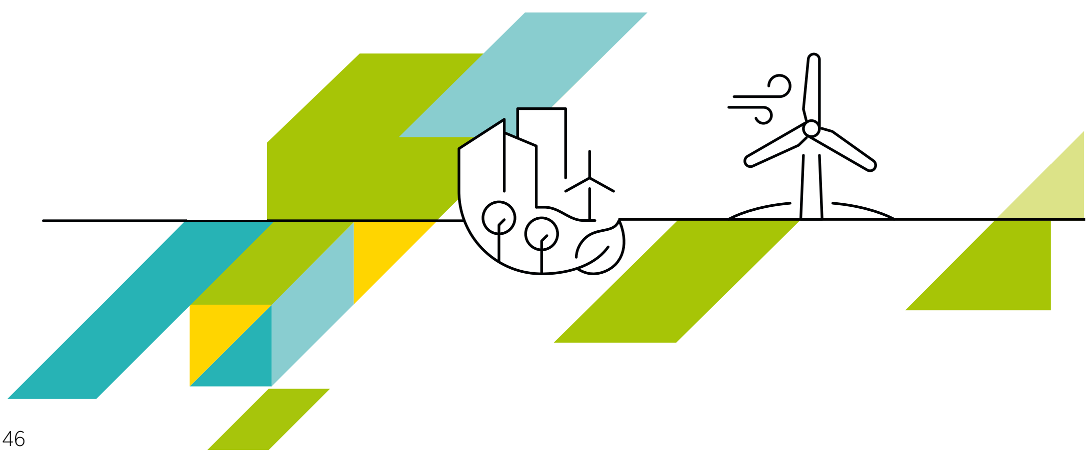
Source: (IRENA, 2024a).
Notes: GW = gigawatt; hydropower data excludes pumped hydro.

Concentration of deployment in a small number of countries or regions should bring the spill-over effect to the other countries and regions, enabling them to capitalise on the opportunities that renewables offer in overcoming development and energy access challenges. Consider Sub-Saharan Africa, where 567 million people still lack electricity access (see Chapter 4). Renewables can expand energy access, and policy makers need to plan for a balanced mix of renewable energy. Tripling global renewable power capacity by 2030 calls for close collaboration and co-ordination among governments, private sector players, multilateral organisations, countries and regions. Front runner countries and mature markets can support emerging markets and developing economies by providing financial assistance, sharing peer-to-peer knowledge and technical know-how, and outlining the parameters of an enabling environment for the scale-up of renewable solutions. These efforts will help unlock renewable power deployment and grid integration.

FIGURE 2.3 **Renewable power capacity additions in G20 and rest of the world, 2015 – 2023**

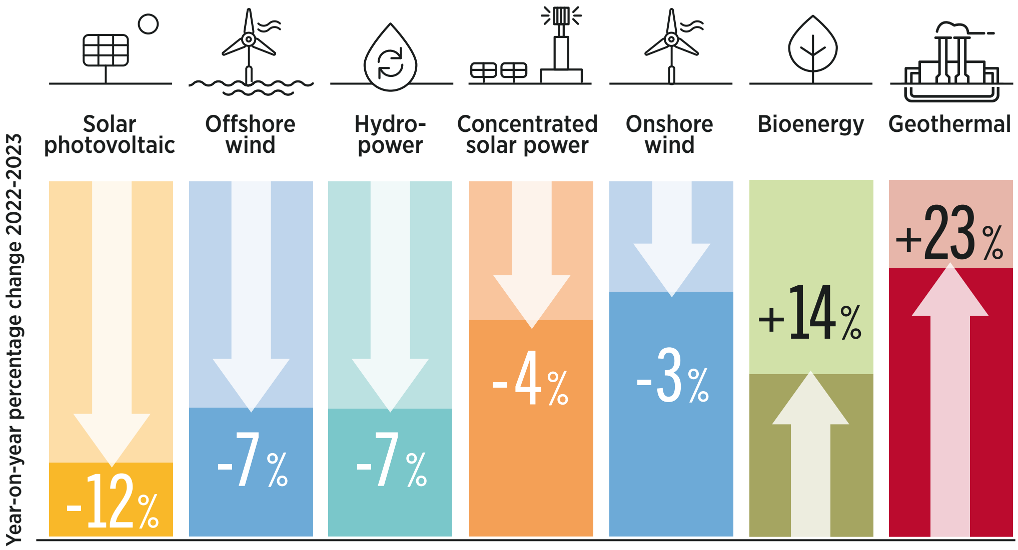


Source: (IRENA, 2024a).
Note: GW = gigawatt.



In 2023, the year-on-year global weighted average of levelised cost of electricity (LCOE) decreased for all technologies except bioenergy and geothermal (Figure 2.4). Solar PV, the most widely deployed technology, saw the steepest drop in LCOE. The cost of offshore wind and hydropower declined, countering the rise observed in 2022. For many areas, the falling costs of renewable electricity made it the most economical choice for power generation. In 2023, 382 GW of renewable power generation capacity produced electricity at a lower cost than the cheapest source of new fossil-fuel-based capacity. These 382 GW represented 81% of the total global increase in renewable power generation capacity. The new projects deployed in 2023 will generate a cumulative undiscounted savings of at least USD 409 billion over their lifetimes (IRENA, 2024b).[2] The growing competitiveness of renewable power generation costs is crucial for achieving the tripling goal by 2030.

FIGURE 2.4 **Global weighted average LCOE reduction per technology between 2022 and 2023**



Source: (IRENA, 2024b).

Notes: LCOE = levelised cost of electricity. The colour shading indicates the year-on-year percentage LCOE reduction (increase or decrease), starting from top (0%) to bottom (25%).

2 Savings are calculated based on the weighted average LCOE of fossil fuel in 2023 compared to renewable electricity generated globally since 2000.

2.1.2 Tracking progress towards tripling renewable capacity by 2030

Tripling renewable power capacity by 2030 is technically feasible and economically viable, but it requires commitment, policy support, investment at scale and project development at speed. IRENA's monitoring and analysis of renewable energy development and deployment show that the technological maturity achieved in the field of renewables – underpinned by enabling policies, competitiveness and widespread resources – has positioned the industry at the very heart of strategies for climate, development and energy security.

The *World Energy Transitions Outlook 2023*, followed by the COP28, IRENA and Global Renewables Alliance joint report, highlighted the need to increase global installed renewable power generation capacity threefold between 2022 and 2030 (COP28 Presidency *et al.*, 2023), as illustrated in Figure 2.5.

The call within the Outcome of the First Global Stocktake at COP28 to triple global renewable energy capacity by 2030 is a critical milestone in the energy transition; working towards it will help keep the 1.5°C goal within reach. Since 2015, annual renewable power add-ons have outpaced new fossil fuel and nuclear power installations combined (Figure 2.2). Yet the pace falls short of that required to meet the 2030 renewable power target of 11.2 TW. To stay on track, net average annual additions of 1044 GW (at a compound annual growth rate [CAGR] of 16.4%) are needed through 2030, as shown in Table 2.1.

While new capacity additions of onshore and offshore wind, hydropower, geothermal, bioenergy and ocean energy lagged in 2023, solar PV deployment, at 347 GW added, is on track to hit the 5.5 TW needed to meet the tripling target. Net annual additions of 578 GW of solar PV capacity seem achievable considering the technology's cost competitiveness (see Table 2.1) and global manufacturing capacity across the supply chain. The impressive growth of global solar PV suggests that, given the right policy environment and economic incentives, other renewable power capacity additions could grow to meet the 2030 target.

These projections for renewable electricity capacity have profound implications for the installed capacity of fossil fuel power generation. By 2030, net fossil fuel capacity will need to drop by 1740 GW. In contrast to an aging fleet of oil and gas power generation, the coal fleet is relatively new, and the 1.5°C Scenario risks stranding coal assets (GEM, 2024). A successful transition from fossil fuels to renewables rests on a host of solutions and technology. A holistic transformation of the power system incorporates various technologies.

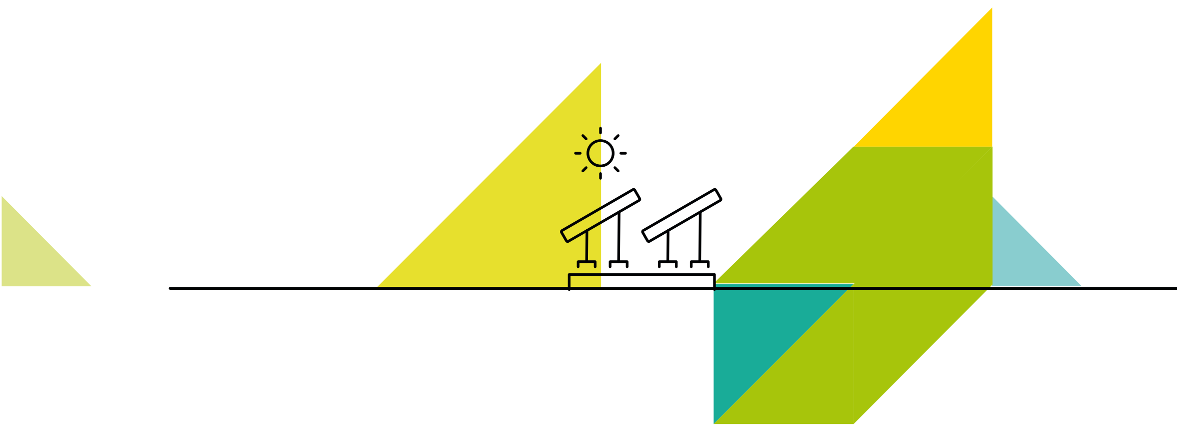
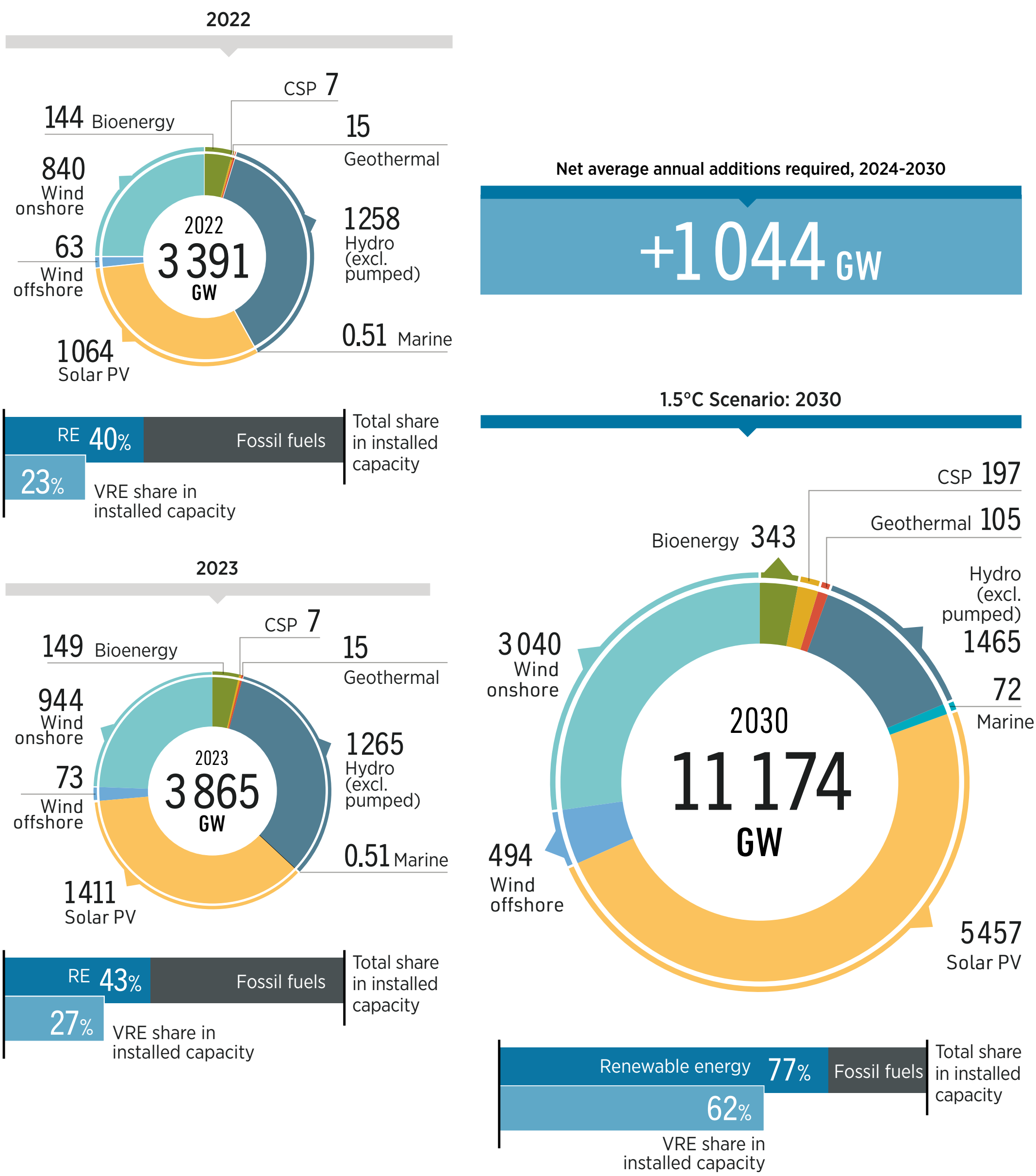


FIGURE 2.5 Global installed renewable power capacity under the tripling goal, 2022, 2023 and 2030



Based on: (IRENA, 2024a).

Notes: CSP = concentrated solar power; GW = gigawatt; PV = photovoltaic; VRE = variable renewable energy; RE = renewable energy; bioenergy includes biogas, biomass waste and biomass solid; hydropower data excludes pumped hydro; tripling target for the global installed capacity by 2030 is compared to 2022 status; the discrepancy between the sum of individual technology category data and the total installed capacity is attributable to rounding adjustments.

TABLE 2.1 Tracking COP28 outcomes: Tripling global renewable power capacity by 2030

Tripling renewable power capacity – **KEY INDICATORS**		2022 [1]	2023 [1]	1.5°C Scenario 2030
RENEWABLES	Total installed renewable capacity (GW)	3 391	3 865	11 174
	Renewables share in installed capacity (%)	40%	43%	77%
	Renewable energy share in generation (%)	28% [2]	29% [3]	68%

ANNUAL AVERAGE CAPACITY ADDITION (GW/year)		2022 [1]	2023 [1]	1.5°C Scenario 2024-2030 [4]
RENEWABLE CAPACITY ADDITIONS	Renewable power capacity additions (GW)	308	473	1 044
	Annual solar PV additions (GW/yr)	200	347	578
	Annual wind energy additions (GW/yr)	79	114	360
	Annual hydropower additions (GW/yr)	23	6.6	29
	Annual bioenergy power additions (GW/yr)	5.9	4.6	28
	Annual geothermal power additions (GW/yr)	0.2	0.4	13
	Annual CSP additions (GW/yr)	0.2	0.3	27
	Annual marine energy power additions (GW/yr)	0.002	0.002	10

Notes: GW= gigawatt; yr = year; PV = photovoltaic; csp = concentrated solar power; hydropower data excludes pumped storage; the discrepancy between the sum of individual technology capacity addition data and the total renewable power capacity additions is attributable to rounding adjustments.

[1] Based on (IRENA, 2024a).
[2] Data for 2021.
[3] Data for 2022.
[4] Annual average capacity additions from 2024-2030 under 1.5°C Scenario.

2.1.3 Assessing the capacity gap: Global perspective

According to IRENA's Planned Energy Scenario (PES),[3] global renewable power capacity is expected to reach 7.4 TW by 2030, still short of the target by more than 30%. Stronger policies are therefore required for under-prioritised technologies beyond solar and wind. Based on analysis of existing energy policies, plans and national targets, goals for renewable power capacity would almost double the 2023 capacity. Yet the Planned Energy Scenario would deliver just 48% (3.5 TW) of the capacity needed to meet the target, requiring an additional capacity of around 3.8 TW. While solar PV and wind energy are at the forefront of national renewable energy targets, other dispatchable renewables are receiving less attention. Figure 2.6 explores possible trajectories for global cumulative renewable capacity.

Solar PV

For its part, solar PV growth is on course to triple renewable energy by 2030. To meet the target, installed solar PV capacity would scale up four-fold from 2023 to reach slightly less than 5460 GW, with a net average annual addition of 578 GW (CAGR of 21%). The absolute growth trajectory would feature an impressive 347 GW annual addition of solar PV capacity, as observed in 2023 and continuing until 2030. Cumulative solar PV capacity would reach almost 3840 GW by 2030. This is around 1600 GW (30%) less than the capacity required under the tripling target. Recent performance demonstrates, however, that solar PV can even exceed the 1.5°C pathway. An average annual addition of 655 GW (CAGR of 23%) under an accelerated growth trajectory puts solar PV slightly ahead of the trajectory needed to achieve the 1.5°C Scenario, with a surplus of around 540 GW. With solar module prices at a record low of USD 0.14 /watt (Lore, 2023) and enough module manufacturing capacity per year, solar PV is set to play a pivotal role in meeting global renewable energy goals towards a sustainable future. The *Global PV Market Outlook* by Bloomberg New Energy Finance (BNEF) also estimates global solar PV cumulative capacity would reach around 5.5 TW this decade (Chase, 2024). Given the pace of solar PV deployment, particularly in China, added focus will be placed on the role of this renewable technology - as well as energy and battery storage - in the next edition of the Outlook.

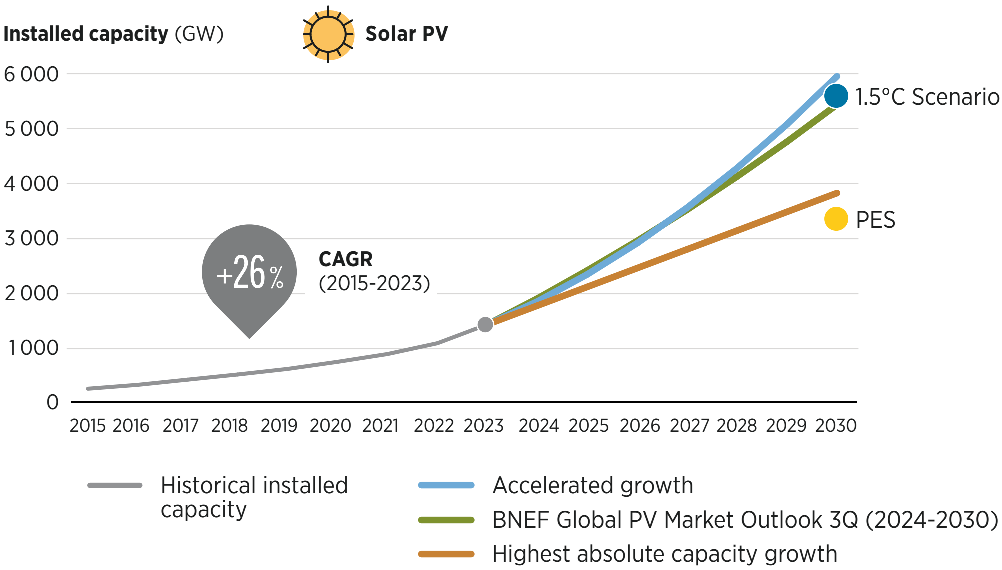
Wind

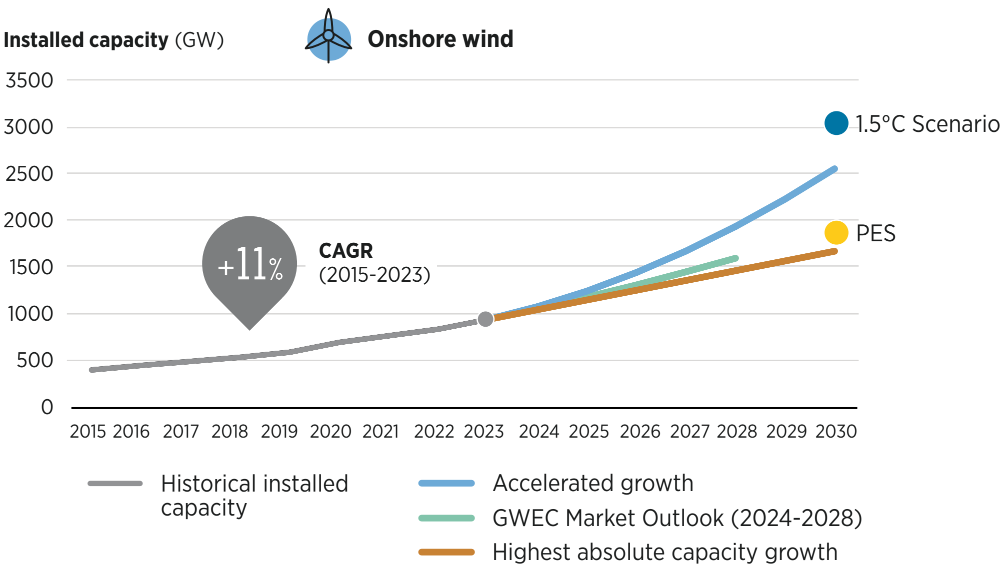
In contrast to solar PV, wind (onshore and offshore) and other renewable energy technologies anticipate deficits. This has in effect been expanding the annual gap between the 1.5°C Scenario and projected trajectories. Annual additions of onshore wind capacity are off track. High equipment costs have combined with supply chain constraints, inflation, permitting delays and unsupportive government policies and regulations (GWEC, 2024). As a result, installed capacity for onshore wind now needs to triple by 2030. The 2023 level of 945 GW will now have to reach 3040 GW, with a CAGR of 18%, requiring average net annual additions of 299 GW of onshore wind capacity from 2024 until 2030. The Global Wind Energy Council (GWEC) *Global Wind Report 2024*[4] expects average annual installations of 130 GW over the next five years (2024-2028), which is around 44% of the annual addition required under the 2030 goal to triple renewable power capacity. PES remains 38% short of goals, so additional capacity of around 1160 GW is needed to realise the tripling goal. Under the absolute capacity growth and the accelerated growth trajectories, cumulative capacity is expected to reach around 1670 GW and 2550 GW by 2030, respectively. Although this falls short – by 45% and 16%, respectively – of the tripling target under the 1.5°C pathway, it highlights the impact of policies and investment on onshore wind technology.

3 The PES is the primary reference case. The PES mentioned in this section is the ongoing updated analysis based on information collected from government energy plans and other planned targets and policies as of August 2024; it focuses on G20 nations.

4 GWEC's Global Wind Report 2024 presents the industry perspective highlighting the expected installations of new capacity over the next five years. The outlook is prepared based on the inputs collected from regional wind associations, industry experts, GWEC members, and takes into account government targets, announced auctions plans, tender outcomes, and existing project pipelines (GWEC, 2024).

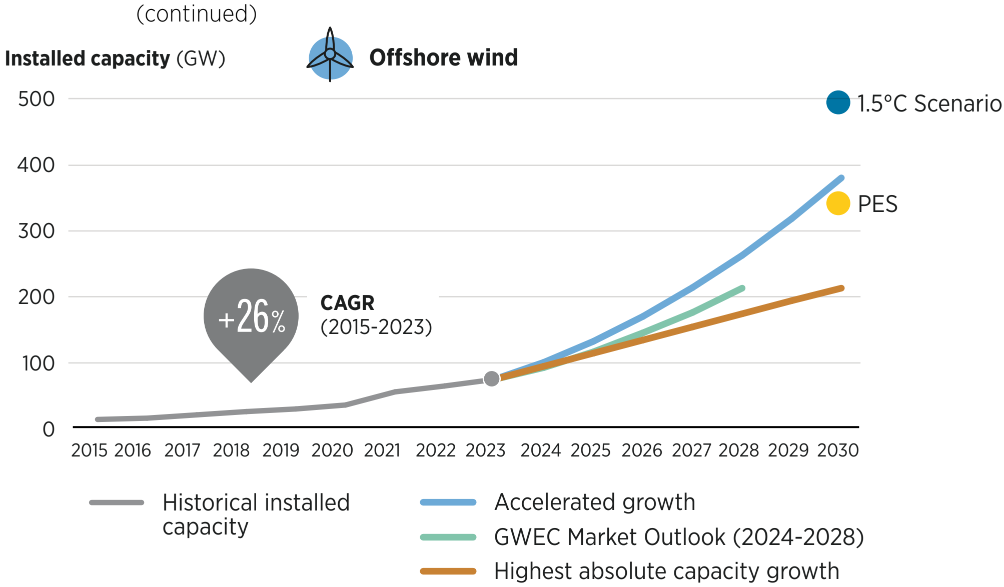
FIGURE 2.6 Global cumulative renewable power capacity projections by technology: Historical trajectories, Planned Energy Scenario and 1 .5°C Scenario (2015–2030)

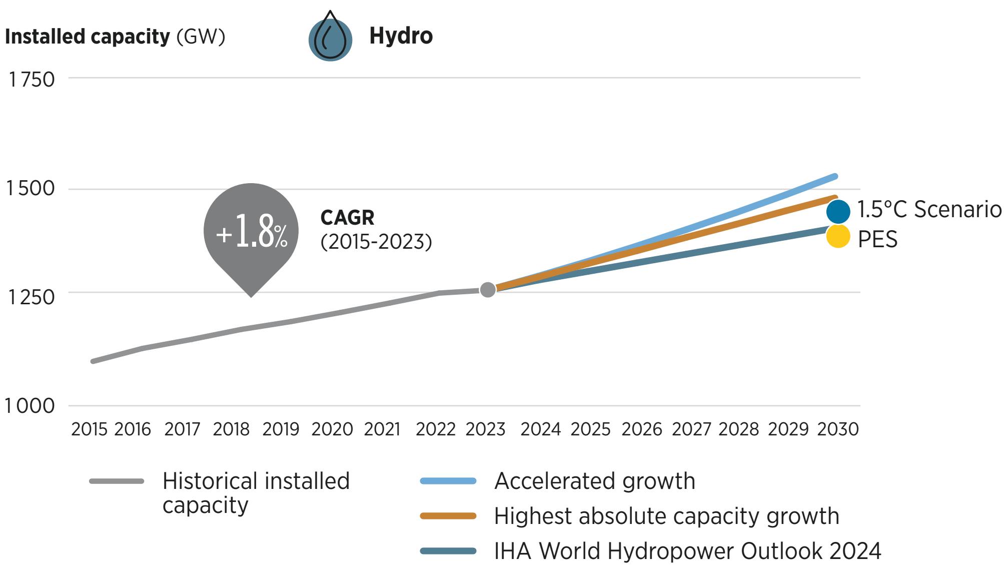




Notes: GW = gigawatt; PES = Planned Energy Scenario, which is based on explicit and implicit country targets, plans information available and collected as of August 2024, and utilises various sources of information from (DCCEEW, 2023; Ember, 2024; ERI, 2023; IRENA, 2023b; OLADE, 2023); 1.5-S = 1.5°C Scenario, which sees a tripling of global renewable electricity generation capacity by 2030. The figure presents the two historical trajectory projections. The 'Accelerated growth' trajectory is based on the historical annual capacity additions of renewable power; the other is based on the highest absolute capacity growth trajectory which assumes that the highest absolute new capacity (GW) addition per technology observed between 2015 to 2023 would be repeated annually to project the capacity from its base in 2023 to 2030.

FIGURE 2.6 Global cumulative renewable power capacity projections by technology: Historical trajectories, Planned Energy Scenario and 1 .5°C Scenario (2015–2030) (continued)





Notes (contd.): It is assumed that if the world can achieve this peak addition once, it could achieve the same addition again in the future. Understanding how the growth rate of annual addition is changing over time between 2015 and 2023 is needed to project future renewable power pathways until 2030. These are only indicative of possible pathways. BNEF has provided solar PV installations forecast in GW_{DC} (direct current), which has been converted to GW_{AC} (alternating current) using inverter load ratio (ILR) assumed to be 1.24.

The renewable target of tripling capacity worldwide would require a seven-fold rise in offshore wind capacity, or 494 GW by 2030, in the 1.5°C Scenario. After falling significantly in 2022, additions of offshore wind capacity recovered in 2023. The 2030 target necessitates average net capacity additions of 60 GW/year between 2024 and 2030 – far more than the 11 GW installed in 2023. On the absolute capacity growth trajectory, with annual deployments of 20 GW over the rest of the decade, the cumulative offshore wind capacity would reach 212 GW. This would fall short, by 57% (282 GW), of the volume of cumulative offshore wind capacity needed to meet the tripling goal. This shortfall shrinks by almost 170 GW along the accelerated growth trajectory, where cumulative capacity is expected to reach 380 GW by 2030. The Global Wind Energy Council (GWEC) *Global Wind Report 2024* expects average installations of 28 GW/year over the next five years, 54% short of the 1.5°C Scenario (GWEC, 2024). Similarly, cumulative offshore wind capacity under PES fails to meet the tripling goal by nearly one-third. While addressing bottlenecks posed, for example, by permitting delays, policy makers must also fortify the wind supply chain and establish a sustainable project pipeline to meet climate goals.

Hydropower

Capacity additions had plummeted in 2023 to 6.6 GW (except for pumped hydro), marking the lowest single-year capacity addition since 2015. Otherwise, capacity addition remained stable at 23 GW (IRENA, 2024a). To meet the target of tripled capacity, hydropower would need to maintain a CAGR of 2.1% to reach 1465 GW by 2030. The global average for annual additions would therefore need to reach almost 30 GW. A repeat of 2016, with its annual capacity addition of absolute 31 GW, would align cumulative capacity with a 1.5°C pathway. Accelerated growth would expand global cumulative capacity to 1500 GW by 2030, surpassing the target by 4%. In the PES, however, the cumulative capacity is short by 4%. To achieve the expected contribution (IHA, 2024), hydropower need to see a modest rise in capacity addition over the average build rate of 20 GW/year through 2030, based on the World Hydropower Outlook 2024. Public acceptance, grid connections, adverse environmental impacts, high investment costs and extended payback times are among the key challenges facing the hydropower industry. Urgent action could close the gap.

Pace and scope of growth

The electricity generation mix will depend on available resources and local requirements for grid stability and energy security. Bioenergy, geothermal, CSP (often coupled with thermal energy storage in real-world applications) and ocean energy are also expected to play important roles in decarbonising the power sector, largely because they could provide relatively more predictable electricity output compared to solar PV and wind power. In the 1.5°C Scenario, average annual bioenergy capacity of 28 GW would have to be deployed through 2030, reaching almost 345 GW, or a six-fold rise over the 2023 additions.

To lower installation costs and achieve climate goals, countries need to promote less mature renewable technologies. They need technology-specific policies and regulatory frameworks, government support, more research and development, and innovative financing models to diversify all forms of renewables. Otherwise, shortfalls will have to be addressed by solar PV and other reliable renewables.

Promoting less mature renewable technologies in the long run is essential to lower installation costs and increase deployment rates, which are crucial for meeting climate goals. Achieving this requires targeted, technology-specific policies, a supportive regulatory framework, government backing, enhanced research and development, and innovative financing models that can drive the exponential growth of these emerging technologies. While established technologies like solar PV will remain essential to the global renewable energy mix, less mature technologies can help diversify and enhance the resilience of energy systems, especially in regions where they can be deployed effectively, such as OECD (Organisation for Economic Co-operation and Development) countries. In contrast, more mature renewable solutions are crucial for addressing the renewable energy gap in EMDEs (Emerging Market and Developing Economies), where scaling up renewables is critical to meeting both climate and development goals.

Tripling renewable power capacity will also require:

- accelerated investments in infrastructure and system operations (*e.g.* power grids, storage);
- updated policies and regulations (*e.g.* power market design and regulation, streamlining permitting);
- measures to strengthen supply chains and develop transition-related skills; and
- scaled up investment, including public funds (see Chapter 4).

2.2 Assessing the gap in physical infrastructure development

As noted elsewhere in this chapter, the path to tripling renewable capacity by 2030 calls for more of everything: grid expansion and modernisation, more interconnections among neighbouring countries, more energy storage capacity, and improved policies, regulations, system operation and perhaps also a reorganisation of the power industry.

Transitioning the current power system from fossil fuels to renewables requires stronger power grid networks (transmission and distribution) to support stable and reliable operations. The aim of modernising the physical and digital infrastructure of power systems is to increase grid flexibility. This can be provided by energy storage solutions, demand-side management, and sector coupling technologies and strategies, which future grids will need to accommodate high shares of variable renewable energy sources. In addition, modernising the power system will enable cost-efficient operations, thus ultimately providing low- or zero-carbon electricity at affordable costs to all.

In the 1.5°C Scenario, power generation requirements would expand by nearly 40% by 2030 from the 2022 level. This rise would require a stronger transmission and distribution infrastructure able to deliver generated power efficiently from optimal sites for renewable resources to demand centres. Yet, despite a significant amount of renewables power generation capacity having been added in the power mix over the decade, the constrained physical grid capacity has led to deployed renewables not meeting their full potential in many cases (McKinsey & Company, 2024). To overcome these hurdles to grid connection and improve operations, power generation needs to embrace an integrated grid expansion planning that harnesses advanced technologies and operational practices (McKinsey & Company, 2024).

Energy storage is key in a decarbonised power system powered dominantly by variable renewable energy sources. It can help stabilise the grid operations and lower costs by providing ancillary services to the power market and through energy arbitrage (see Chapter 3). Pumped hydro storage dominates, with around 142 GW of capacity by 2023 (IRENA, 2024a). In the 1.5°C Scenario, capacity would need to expand to 320 GW by 2030, a more than two-fold rise. Much more storage would be required, however, for long-term decarbonisation and to meet the tripling target. Grid-scale battery storage could bridge that gap if capacity grows from 86 GW in 2023 (IEA, 2024f) to between 360 GW and 900 GW by 2030, where the amount deployed depends on the rollout of complementary flexibility assets such as demand side management (DSM) measures, interconnection and sector coupling (IRENA *et al.*, 2024). Grid-scale battery storage systems are an emerging technology, although they are not yet cost-competitive with fossil fuels (Rodby, 2022). Recent trends hold promise: from 2010 to 2023, battery storage costs fell by nearly 90%, from USD 2 511 to USD 274 per kilowatt hour (kWh) (IRENA, 2024b). But further decreases are needed to meet demand. Government intervention may prove essential to de-risking the technology and reducing its costs. Beyond battery storage and pumped hydro systems, other innovative energy storage technologies and systems will need to be further developed.

2.3 Progress in the electrification of end-use sectors and energy efficiency

2.3.1 Optimising the energy transition: The synergies of electrification and energy efficiency

A rapid scale-up in renewables is only part of the energy transition. The transition should also aim to dampen energy intensity. The interactions between electrification and energy efficiency play a vital role in decarbonising across sectors. Electrification combined with energy efficiency can lower CO_2 emissions. Heat pumps, for example, can leverage renewable electricity to lower emissions. In buildings, the shift to electric appliances, when paired with well-designed insulation and energy-efficiency, can cut energy demand and promote renewable energy. In the transport sector, EVs consume less energy than vehicles powered by internal combustion. Smart grid technologies optimise energy distribution and consumption by improving load management and reducing peak demand. The interplay of electrification with greater energy efficiency supports a sustainable energy future.

Doubling energy efficiency by 2030 is essential for climate and economic targets, requiring broad adoption of efficient technologies, structural and behavioural shifts, and sector-wide measures (see Table 2.2). These efforts not only cut energy demand but also bring economic and environmental benefits like emission reduction, less road congestion, and better air quality through transitions to public transit, rail, circular economy practices, and efficient buildings and vehicles.

2.3.2 The nexus of energy efficiency and electrification in buildings, transport and industry: Recognising existing gaps

Developed and developing countries show persistent disparities in energy efficiency. Many countries lack the necessary infrastructure, technology and financial resources in improving energy efficiency faster than they currently do. Governments should drive progress with standards, subsidies and tax incentives that promote investments in energy-efficient technologies and encourage behavioural changes. Investments in research and development by the public and private sectors are also key.

Buildings, transport and industry can decarbonise with heat pumps, efficient appliances and EVs – aided by flexible electrification strategies and decentralised energy.

Progress in transport electrification in 2023 fell short of the required pace. Accelerating the uptake of EVs, along with power supply decarbonisation, is by far the most important lever for the sector's decarbonisation. Technological progress on battery evolution has secured the economic case for EVs in recent years, and the scope of application is quickly expanding to a broader set of road vehicle segments and service types. Almost 14 million electric and plug-in-hybrid vehicles were sold worldwide in 2023, a 31% increase from 2022 (REN21, 2024). Successful launches of new EV models, financial incentives and better charging infrastructure have been strong drivers; yet the current battery EV and plug-in hybrid EV stock would need to rise to 360 million by 2030 from 40 million today, a target that cannot be achieved at current growth rates. In the 1.5°C Scenario, the electrification rate of global transport would rise to almost 7% by 2030, with EVs accounting for more than 19% of all road transport modes. Some G20 nations already have strong targets to reduce fossil fuel dependency in the transport sector. An example is the plan to ban CO_2-emitting cars as of 2035 in the European Union (European Council, 2023). Other countries have yet to set targets that align with the 1.5°C Scenario.

TABLE 2.2 Tracking global energy efficiency and electrification of end-use consumption by 2030

	Indicators	Recent years	PES Scenario 2030 [1]	1.5°C Scenario 2030	Progress (off/on track)
ENERGY EFFICIENCY	Energy intensity improvement rate (%)	2% [2]	2% [3]	4% [3]	
	Building renovation rate (% of stock per year)	1% [4]	1%	2%	
ELECTRIFICATION OF END-USE CONSUMPTION	Electrification rate in TFEC (%)	23% [5]	23%	30%	
	Electric and plug-in hybrid light passenger vehicles stock (million)	40 [6]	255	360	
	Heat pumps in buildings (GW)	1280 [7]	1943	8937	
	Heat pumps in industry and in DH systems (GW)	No data/ negligible [8]	16	434	

Notes: PES = Planned Energy Scenario; DH = district heating; GW = gigawatt; TFEC = total final energy consumption

[1] PES analysis is as of March 2023.

[2] Energy intensity improvement achieved in 2022 (IEA, 2024b) for primary energy supply, and (CE, n.d.) for GDP historical statistics.

[3] Average annual improvement rate from 2023 to 2030 (IEA, 2024b) for primary energy supply, and (CE, n.d.) for GDP historical statistics.

[4] Estimated percentage of renovated buildings in the global stock in 2021.

[5] 2022 value, (IEA, 2024).

[6] 2023 value (BNEF, 2024a).

[7] 2023 value estimate (IEA, 2021b, 2024d).

[8] No database of industrial heat pumps is available today (Schlosser *et al.*, 2020). They are assumed to have negligible share of the total final energy consumption in industrial process heat supply (Agora Energiewende, 2023).

More than three-quarters of the building stock in developed markets is poorly insulated. Worse, buildings are heated on conventional fossil fuel technologies. Major gains could be realised through a deep renovation of the building stock. By 2030, over 80% of the stock in developed markets, 60%-80% in developing markets and close to 50% in emerging markets must meet higher efficiency standards. Building renovation rates increase from less than 1% per year in 2021 to 2% per year by 2030 in developed economies; meanwhile, in developing countries and emerging markets, they remain at 1% (IRENA, 2023). The transition to net-zero buildings would require reduced energy demand of existing and new buildings, as well as policies to promote the electrification and direct use of renewables for heating and cooling. Customary policies in this sector include building codes; bans on the use of fossil fuel for heating; financial and fiscal incentives for renovation, efficiency and renewables; targets for net-zero buildings; minimum energy performance standards for appliances and mandates for solar hot water for public buildings.

By 2030, the increased electrification of heating in cold regions, growing demand for cooling in warm climates and wider adoption of electric cooking in urban areas would almost double electricity demand compared with 2021. In the 1.5°C Scenario, the total installed capacity of heat pumps in buildings is estimated to rise to around 9000 GW by 2030 from around 1300 GW in 2021. Global sales of heat pumps in buildings saw an 11% increase in 2022, marking the second consecutive year of double-digit growth for this pivotal technology in the transition to secure and sustainable heating solutions.

Large-scale heat pumps in industry and district heating systems have considerable potential. Heat pumps used in district heating and industry have capacities exceeding 100 kW up to multiple megawatts in heat supply output (European Heat Pump Association, 2019). Despite the lack of data on their deployment (Schlosser *et al.*, 2020), we can nevertheless estimate their share at or near 0% of global heat supply (Agora Energiewende, 2023). Still, they are gaining traction in worldwide, particularly in industry and district heating and cooling systems for Europe, Japan and China (Euroheat & Power, 2022; Werner, 2017). A sizable gap remains between current capacity and that required (434 GW) for district heating and industrial process heat supply systems by 2030. While some progress can be made between now and then in district heating, the rate of their deployment in industrial process heat supply is expected to remain low in 2030. There are few market-ready solutions for heat requirements above 100°C (Zühlsdorf, 2023). In the coming years, it will be important to invest in large-scale heat pumps for industry, create an enabling regulatory environment and strengthen collaboration among stakeholders, including manufacturers and vendors, industries, utility companies, research institutions, service providers and government. Governments should take the lead with policies and financial incentives that help to phase out fossil-fuel-based heat supply and lower electricity-to-fossil-fuel price ratio for heat production. Sweden, Denmark, Finland and Germany have all deployed large-scale heat pumps in buildings and district heating due to favourable policies and low electricity prices for heat production purposes.

2.4 Progress in finance and investments

2.4.1 Current status

In 2023, global investments surpassed USD 2 trillion in energy transition-related technologies,[5] another record high (Figure 2.7). The top recipients were China (48%), the United States (17%), Germany (5%), the United Kingdom (4%) and France (3%). Global investments rose 17% in 2023 compared to 2022. The European Union led growth, followed by the United States, and appears to have been driven by expansionary fiscal policies such as the RePowerEU (European Green Deal) and the Inflation Reduction Act, which instituted favourable policy instruments for energy transition technologies, tax credits, grants, rebates and public procurement (Moody's Analytics, 2022). These have all helped balance the downward pressures on investments – at least in developed economies – exerted by contractionary monetary policies that hiked interest rates (Wood Mackenzie, 2024a), supply chain disruptions and permitting issues. Many emerging and developing economies (EMDEs) face increased difficulties in attracting financing, exacerbated by shrinking fiscal capacity and rising debt burdens (see section 4.1).

Electrified transport (mainly EVs and charging infrastructure) attracted USD 634 billion in 2023 (31% annual increase) (BNEF, 2024a). Most of the investments and sales take place in China, the United States, Germany and the United Kingdom. But in recent years the fastest-growing markets are seen in India, Indonesia and Thailand (REN21, 2024). Record growth in EV investments is spurred by upfront price subsidy/grants, value-added tax exemption, rebates, and other tax and financial incentives for manufacturing (Martins *et al.*, 2023).

With charging infrastructure expanding in certain markets, consumers can more readily adopt EVs (Martins *et al.*, 2023). Widespread adoption would rely on accessible and affordable charging infrastructure in public areas for people without charging units at home (IEA, 2024e). In 2023, USD 31 billion was invested in charging infrastructure, dominated by China – an almost four-fold rise from 2020 (BNEF, 2024a) (Figure 2.8). Public charging infrastructure investments were estimated to be just 23%, while the remaining comprised home charging infrastructure (BNEF, 2024a).

Global investments in renewable power reached USD 570 billion compared to USD 448 billion in 2022, a 27% increase during 2023 (IRENA, 2024b). Major markets include China, the United States, Brazil, India and Germany. Investments in solar PV, onshore wind, and offshore wind totalled USD 387 billion, USD 116 billion and USD 30 billion, respectively. As in previous years, solar PV remains the most-funded technology, representing 68% of global investments. Hydropower,[6] bioenergy, CSP and geothermal are falling behind, accounting for investment values of USD 21 billion, USD 13 billion, USD 2 billion and USD 1 billion, respectively.

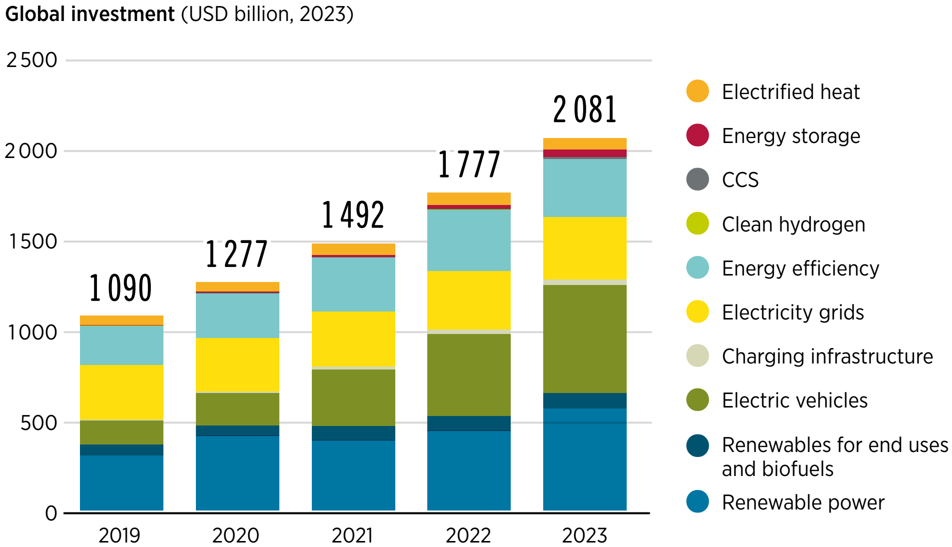
Global investments in energy efficiency – which includes incremental spending on new energy-efficient equipment or the full cost of refurbishments in buildings, industry, and transport – dipped to USD 323 billion in 2023, a 6% drop from the previous year.[7] Energy efficiency measures continue to be adopted, but investments in 2023 were far below the levels needed by 2030.

5 US GDP deflator was used as a proxy for economywide inflation (IMF, 2023a). Unless otherwise stated, all investment numbers in section 2.2 are in USD 2023.

6 Excluding pumped hydro.

7 IRENA estimations based on (IEA, 2024e).

FIGURE 2.7 **Global investment in energy transition technologies, 2019-2023**



Notes: Data for energy transition technologies include renewable energy, electrified heat (mainly heat pumps), electrified vehicles, charging infrastructure, clean hydrogen, carbon capture and storage (CCS), energy storage, and power grids (transmission and distribution). All values are adjusted for inflation and are in constant USD billion 2023 terms. This figure excludes energy conservation investment data for 2023 due to limited data availability for all years; these figures are presented separately in Figure 2.12. Additionally, while this figure includes electric vehicle investments from (BNEF, 2024a), they are excluded from Figure 2.12, where IRENA's methodology to calculate investment in transport sector differs and the total cost of electric vehicles is not considered. Finally, CCS investments here cover sectors beyond power, while those used to estimate investment gaps in figure 2.12 are mainly power-sector-related CCS. CCS = carbon capture and storage.

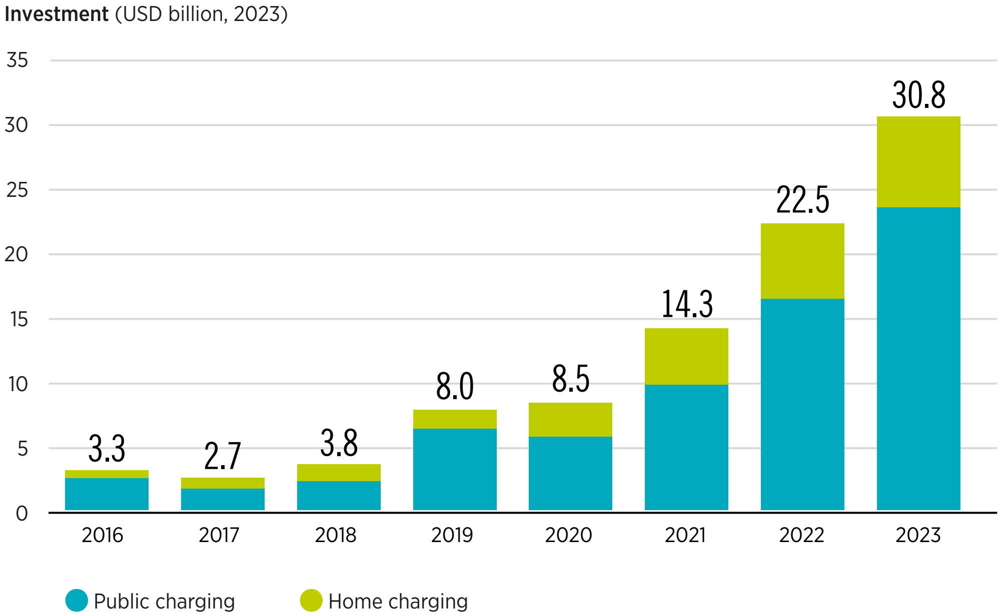
Investments in electricity grids (transmission and distribution) totalled USD 350 billion in 2023, a 7% increase since 2022.[8] North America (mainly the United States), China and Europe make up almost three-quarters of investments in electricity grids. Investments in the United States mainly targeted grid modernisation to adapt to renewable energy production and increased demand from EVs and data centres. Meanwhile, investments in China focused on distribution to connecting areas with large renewable energy production and building inter-regional transmission infrastructure. Countries experiencing growing power demand such as India, Mexico and Viet Nam are investing on the distribution side, while 2024 also saw large-scale transmission projects, *e.g.* a 765 kilometre (km) connection between the United Kingdom and Denmark, and, in Australia, a 900 km connection between New South Wales and South Australia (BNEF, 2024c). Ancillary investments in grid infrastructure (such as those for battery storage – an emerging sector) surged for a second consecutive year to reach USD 41 billion in 2023 (IEA, 2024e). As costs decline, these investments are expected to grow.

The unprecedented policy support provided in previous years continues to encourage investments in electrified heat (mainly heat pumps).[9] Although annual investment levels have plateaued, they remain above the USD 60 billion mark in 2023 (BNEF, 2024a). Policy measures included the European Union's REPowerEU Plan, which mandated the installation of about 20 million heat pumps in the European Union by 2026 and

8 IRENA estimations based on (IEA, 2024e).

9 Electrified heat investments do not include non-residential heat pumps (BNEF, 2024b).

FIGURE 2.8 Investments in EV charging infrastructure 2016–2023



Based on: (BNEF, 2024a).

Note: USD = United States dollar.

60 million by 2030 (EHPA, 2022). In the United States, the US Inflation Reduction Act offered a heat pump rebate, at 100% of the cost of a new heat pump, up to USD 8000 (US DOE, 2024). These rebates were provided to households with incomes 80% below the median, as well as for up to 50% of the heat pump's cost for households with incomes between 81% and 150% of the median. In addition, there was a 30% tax credit of up to USD 2000 on new heat pumps for households with income exceeding 150% of the median (HVAC, 2022).

Meanwhile, clean hydrogen investments – based on projects that reached operation – amounted to just over USD 2 billion in 2023 (IEA, 2024e). The total is expected to soar because large-scale projects that recently reached financial close are expected to begin operating in the next few years. These include the NEOM project in Saudi Arabia (2.2 GW totalling USD 8.5 billion), which reached a final investment decision (FID) in 2023. Policy support for hydrogen is gaining momentum worldwide: as of May 2024, 53 countries had a hydrogen strategy or roadmap in place. Growing interest from investors has seen hydrogen technology receive large inflows of both early-stage private capital and national funding (IRENA and CPI, 2023). But many projects have yet to reach even financial close, let alone operation, as market uncertainty looms. IRENA is supporting member states in designing auctions for green hydrogen to advance projects still stuck in the pipeline (Wood Mackenzie, 2024b).

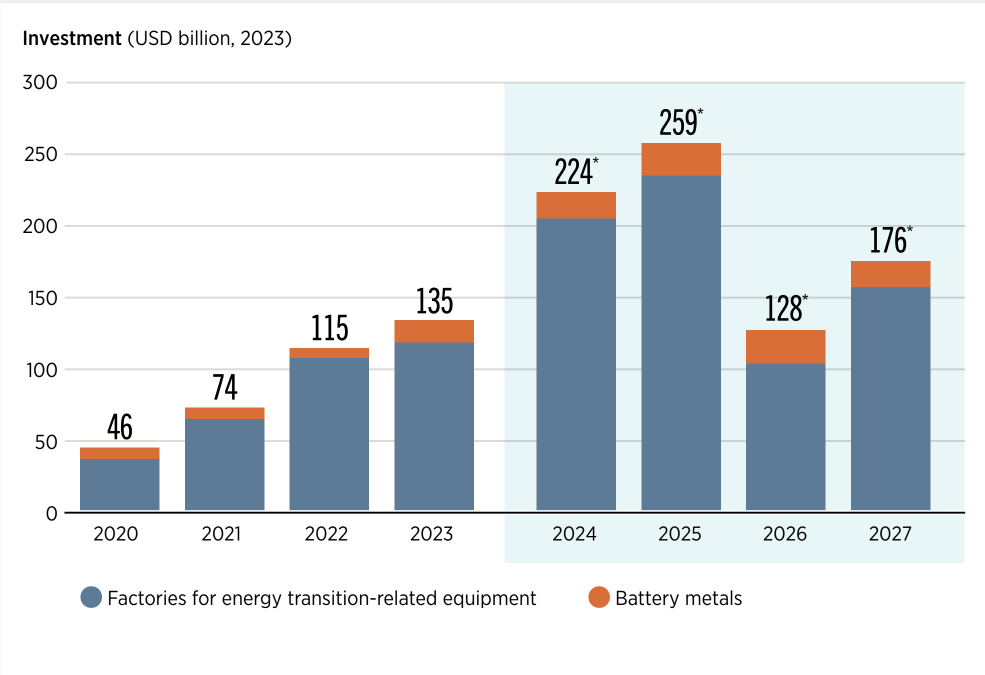
Investments in the energy transition supply chain – including mining and manufacturing of key components (*e.g.* solar modules, wind turbines, battery storage and electrolysers) – will need to keep pace with the requirements of the 1.5°C Scenario. Investments have risen three-fold since 2020 and are expected to continue as the supply chain reaches beyond centres like China (see Box 2.1).

BOX 2.1 Investments in the energy-transition-related supply chain

Annual investments in the global energy transition supply chain grew three-fold, from USD 46 billion in 2020 to USD 135 billion in 2023 (Figure 2.9). Cumulatively, at least USD 370 billion has been invested in the supply chain, with almost 90% going to factories that manufacture related equipment (*e.g.* solar modules, wind turbines, batteries and hydrogen electrolysers). The remaining 10% went to mining of battery metals and refineries for critical materials such as lithium, cobalt and nickel.[10] As mining and manufacturing capacity must keep pace with the deployment of transition-related technologies envisioned in the 1.5°C Scenario, such investments form a crucial building block of the energy transition.

10 Data on some parts of the supply chain for EVs, heat pumps and the wind sector are missing. These numbers represent a lower bound, and the true value of investments in the supply chain is likely higher. But a complete dataset would indicate similar trends for growth and investments.

FIGURE 2.9 Investments in the supply chain related to the energy transition (historical and planned, 2020-2027)



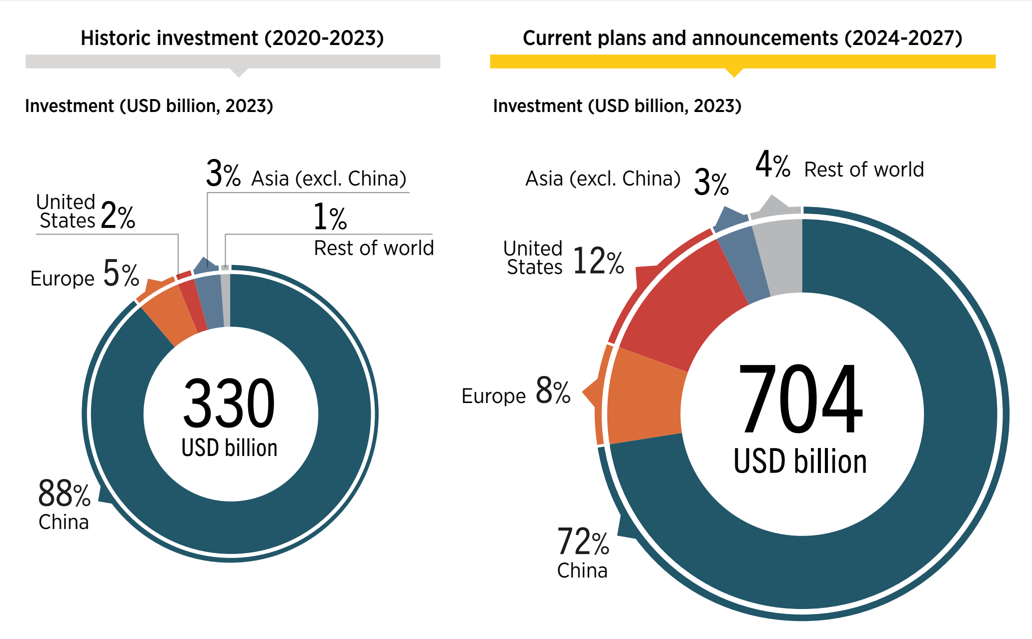
Source: (BNEF, 2024d).

Note: Data for 2024-2027 based on BNEF estimates. The 2026/2027 figures will likely rise as new projects are announced. Therefore, the data for those two years should not be interpreted as an expected dip in investments.

China is the leading supplier of energy transition-related technologies globally, holding more than 60% of the world's manufacturing capacity for technologies such as solar photovoltaic, wind systems and batteries (IEA, 2023c). The country further possesses 40% of electrolyser manufacturing (IEA, 2023c). But other countries are investing large amounts of capital to secure their stake in the energy transition supply chain.

Estimates show that an additional USD 704 billion will be invested through 2027 in factories manufacturing equipment for the energy transition. The United States and Europe are expected to make up for a greater share of investments, at a combined 20.5% (2024-2027), compared to 7.8% between 2020 and 2023. It is estimated that China will have invested at least 72% of this total, compared with its 88% investment stake in 2020-2023 (Figure 2.10). As other governments introduce subsidies and local content requirements to propel domestic manufacturing, factories are emerging outside China, the United States and the European Union, particularly in India, Japan, the Republic of Korea, Türkiye and Viet Nam (BNEF, 2024c). This expansion of the energy transition supply chain will augment energy security and spread socio-economic benefits more broadly. These investments need to be balanced against the environmental impact of mining, displacement of local communities, and sustainable manufacturing and recycling practices.

FIGURE 2.10 Investments in factories for manufacturing energy transition-related equipment by region (historical vs planned)



Note: Data for China* come from Mainland China. Data for other territories could not be disaggregated from Asia (excluding China) group.

2.4.2 Investment gaps

Renewable power capacity can be tripled by 2030. It is technically feasible and economically viable, but achieving this goal requires significant investments. While the technological maturity of renewables and supportive policies have positioned renewables at the heart of climate and energy strategies, a substantial investment gap remains (see Figure 2.12). This section highlights the investments required for the energy transition by 2030 under the 1.5°C Scenario. Achieving the climate objectives requires speeding up of renewable power generation capacity, electrification of end-use sectors and improvement of energy efficiency. Accelerating investments in infrastructure and system operations, such as power grids and storage, is crucial. Additionally, updated policies and regulations, streamlined permitting processes, strengthened supply chains, and the development of transition-related skills are essential. A major scale-up of investment, including substantial public funds, is necessary to bridge this gap and achieve the tripling target (for details see Chapter 4).

As emphasised throughout this chapter, a scale up of investments is required across all sectors for the remainder of this decade (see Figure 2.12). In the 1.5°C Scenario, cumulative investment across the entire global energy system would need to reach USD 47 trillion by 2030, or USD 6.7 trillion per year on average until 2030. Annual investment would need to scale by 2.5 times to remain on the 1.5°C pathway, relative to the USD 2.6 trillion invested in 2023. Investments in energy transition-related technologies and infrastructure amount to 82% of total energy-related investments by 2030.

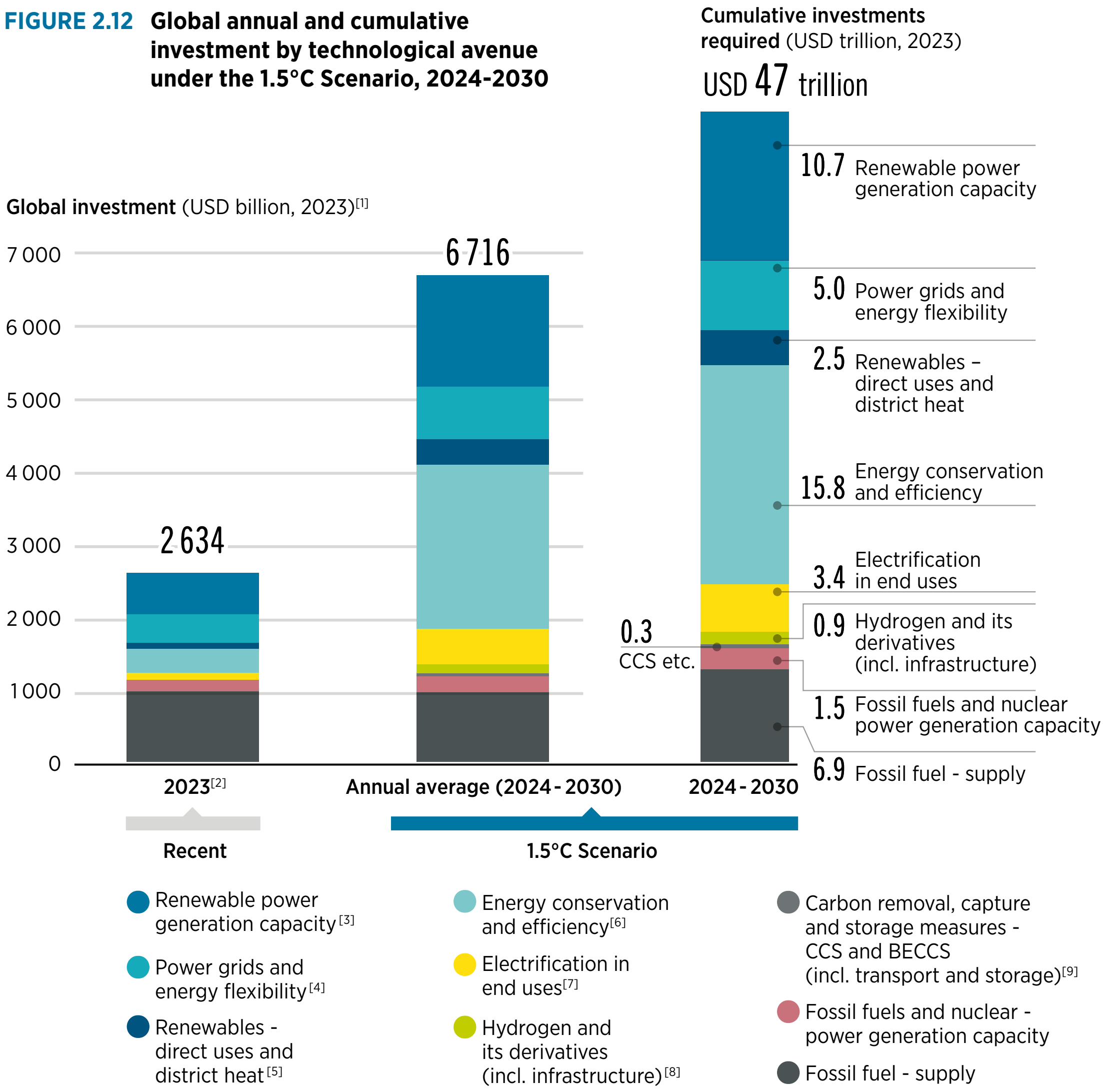
Cumulative investments in moving the power sector towards renewables would amount to USD 15.7 trillion (33% of the total investment) – USD 10.7 trillion on renewable power generation capacity and USD 5 trillion on enabling infrastructure, *i.e.* power grids and flexibility, by 2030.

An average of 1044 GW of renewables capacity must be installed annually through 2030 – more than double the record set in 2023. Annual investments in renewable power generation must surge from USD 570 billion in 2023 to USD 1532 billion on average until 2030 (see Table 2.3). It is important to emphasise that the increase in installed renewable power capacity requires a parallel commitment to significant investment in electricity network and flexibility measures. For several years, investment in electricity grid networks have lagged investments in renewable power capacity. In the 1.5°C Scenario, annual average investment needs in electricity network expansion and upgrade would reach USD 600 billion by 2030, nearly double the investment of USD 350 billion in 2023. An energy storage system is central to a flexible and resilient power system. It calls for annual average investment of USD 41 billion to triple in 2023, up to USD 117 billion per year until 2030.

In end-use sectors, investments in transition-related technologies amount to almost USD 23 trillion, or nearly half the total required energy sector investment between 2024 and 2030. This includes investments in energy conservation and efficiency (USD 15.8 trillion); electrification in end uses (USD 3.4 trillion); production and direct use of renewable technologies (USD 2.5 trillion), hydrogen pipeline, electrolysers and storage facilities (USD 0.9 trillion); and carbon removal infrastructure – carbon capture and storage (CCS) and bioenergy with carbon capture and storage (BECCS) (USD 0.3 trillion).

Investment in fossil fuels supply would account for USD 7 trillion (15%), while investment in fossil fuel and nuclear power generation is pegged at USD 1.5 trillion (3%) by 2030 (see Figure 2.12).

FIGURE 2.12 Global annual and cumulative investment by technological avenue under the 1.5°C Scenario, 2024-2030



Notes: CCS = carbon capture and storage; BECCS = bioenergy with carbon capture and storage
[1] All figures have been adjusted for inflation and are represented in real terms, *i.e.* 2023 US dollars.
[2] (IRENA estimation as of July 2024; BNEF, 2024; WEI, 2023; WEI, 2024; Siepen *et al.*, 2024).
[3] Renewable power generation capacity: Investment in deployment of renewable technologies for power generation.
[4] Power grids and energy flexibility: Investment in transmission and distribution networks (excluding public EV charging stations investments), smart meters, pumped hydropower and battery storage among other energy storage technologies. The average annual investment requirement is based on the lower bound estimates for battery storage capacity of 360 GW.
[5] Renewables - direct uses and district heat: Biofuels supply, renewables direct uses and district heat applications (*e.g.* solar thermal, modern bioenergy) and ammonia and methanol production from biomass.
[6] 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. Vehicle stock investments are excluded. Energy efficiency in buildings: Improving building thermal envelopes (insulation, windows, doors, etc.). Energy conservation: Investments in energy conservation includes those in bio-based plastics and organic materials, chemical and mechanical recycling and energy recovery.
[7] Electrification in end uses: Investments in EV charging infrastructure, heat pumps in industry and buildings and transport.
[8] Hydrogen and its derivatives (incl. infrastructure): Electrolyser capacity (alkaline and polymer electrolyte membrane) for the production of green hydrogen, infrastructure for the transport of hydrogen and hydrogen long duration seasonal storage. Hydrogen based ammonia and methanol: Production of ammonia and methanol from hydrogen feedstocks. Historical number is based on spending on projects that entered operation in 2023 (IEA, 2024e).
[9] CCS deployment, mainly for process emissions in industry and blue hydrogen production. BECCS deployment in chemicals, power and cogeneration plants. Historical number is based on spending on projects that entered operation in 2023 (IEA, 2024e).

TABLE 2.3 Key indicators for tracking energy transition finance and investments through 2030

Parameters	Annual average investments in 2023 USD billion[1]: Historical	Annual average investments in 2023 USD billion[1]: 1.5°C Scenario 2024-2030
Investment in renewable power capacity installations	570[2]	1 532
Investment in power grids and infrastructure upgrades including grid expansion, interconnections and grid flexibility enhancement[3]	350[4][5]	600
Investments in storage technologies – pumped hydro and batteries	41[4][6]	117[7]
Investments needs for charging infrastructure of EVs and EVs adoption support	31[5]	110
Investment needs for heat pumps	63[5]	317
Investments for hydrogen electrolysers and infrastructure	2[4][8]	68

Notes: EV = Electric vehicle; bn = billion; yr = year.

[1] All figures have been adjusted for inflation and are represented in real terms; *i.e.* 2023 US dollars.

[2] IRENA estimation as of July 2024.

[3] Power grid flexibility would allow sustainable management of supply-demand volatility.

[4] Estimation based on (IEA, 2024h).

[5] Based on (BNEF, 2024a).

[6] 2023 investment includes only investment in battery storage.

[7] The average annual investment requirement is based on the lower bound estimates for battery storage capacity of 360 MW.

[8] Estimation based on project entered operation in 2023.

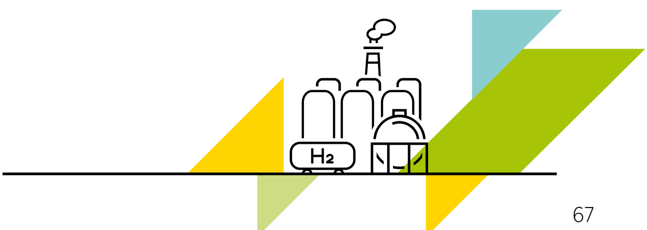
Despite record growth in 2023 for renewables, the energy transition remains off track because of structural barriers and underinvestment. Achieving the global target set at COP28 to triple renewable power capacity by 2030 requires an additional 7.3 TW. An average of USD 2.2 trillion a year is required between now and 2030 to expand renewable power generation capacity, enhance and modernise power grids and create flexibility (see Table 2.3).

The EV market exemplifies this need. In 2023, around 20% of all cars sold worldwide were electric, indicating a growing consumer preference for EVs. As their popularity rises, so will demand for charging infrastructure. Investing in this infrastructure through 2030 is crucial. Total investments in transport need to rise to USD 2.1 trillion to 2030, or 6% of all transition-related investment. EV charging infrastructure would account for 25% of this total, while energy efficiency would represent 34%, transport electrification 13%, and hydrogen stations and bunkering facilities the remaining 28%.

The steady deployment of residential heat pumps remains key, while heat pumps for district heat and industrial process heat supply are essential. In the 1.5°C Scenario, USD 2.2 trillion would flow to all heat pumps – residential, district heat, and industry – in 2024-2030. Just under 90% of this would go to residential and the rest to district heat and industry. Each year, USD 317 billion would be required until 2030, on average, to achieve the required investment level.

Early investment in the clean hydrogen supply chain (electrolysis, fuel cells, transport pipelines, storage caverns, *etc.*) is vital to the uptake of hydrogen applications in end-use sectors and to carbon reduction goals. Green hydrogen could be key in mitigating emissions from harder-to-decarbonise sectors such as aviation, shipping and heavy industry, where direct electrification is nearly impossible. Globally, the emergence of a green hydrogen system is key both to meeting demand from these end-use sectors and to delivering electrolyser capacity expansion. In the 1.5°C Scenario, green hydrogen would amount to 40% of hydrogen consumption in 2030 from the current around 1%. An expansion on this scale requires rapid evolution of the hydrogen supply value chain; USD 0.5 trillion would need to be invested in green hydrogen production and infrastructure by 2030. This means, on average, USD 68 billion every year in the coming seven years. It is important to note that although 2023 saw the highest level of investment in hydrogen production and infrastructure – projects reaching FID amounted to USD 9 billion (BNEF, 2024b) – those entering operation that year were worth just above USD 2 billion (IEA, 2024e). Far below the required annual level, this will need to be more than 25 times higher through 2030.

To scale up the use of clean hydrogen in end-use sectors requires infrastructure. The transport of hydrogen via pipelines requires upgraded infrastructure, whose costs may limit their viability. Yet the demand for clean hydrogen is such that dedicated networks may be inevitable. 125 Mt of clean hydrogen would be required under the 1.5°C Scenario, of which 60% are blue hydrogen as an interim solution. Green hydrogen production would need to scale up after 2030.



CHAPTER 03

OVERCOMING KEY BARRIERS: **POWER SECTOR FLEXIBILITY**

KEY POINTS

- With the increasing share of variable renewable energy (VRE) in power systems, modernising energy infrastructure must primarily focus on enhancing grid flexibility to improve the reliability and cost effectiveness of future system operations. This also suggests that investments in grid enhancement and upgrading along with continued expansion need to be significantly increased.
- There are various options for enhancing power system flexibility. The applicability of these options often depends on system characteristics, flexibility needs, interconnectivity and inter-operability with neighbouring systems and the economics of flexibility options, among other key factors.
- Achieving a 100% renewable electricity supply is possible but presents challenges for large and complex power systems within the current technological context. Finding suitable solutions to challenges arising in systems operating with 100% VRE over a longer period requires further research and development.
- To overcome existing and emerging barriers, it is crucial to create an enabling framework that supports greater flexibility and electrification in the power sector, alongside technological advancements. Key elements of this framework include establishing clear targets and strategies, updating electricity market structures and rules to foster an environment conducive to increased system flexibility, and designing and implementing policies that accelerate direct and indirect electrification.

03

3.1 The infrastructure needed for flexibility and reliability in VRE-based systems

In IRENA's 1.5°C Scenario, renewable energy sources are projected to supply 91% of global electricity by 2050, with solar photovoltaic (PV) and wind accounting for approximately 70%. To support this shift, the power sector requires significant infrastructure developments to ensure stable, reliable and efficient operation of grids based dominantly on VRE. These developments involve not only expanding existing infrastructure to accommodate the increasing generation capacity, but also modernising current assets and updating operational and planning practices. This modernisation is essential for providing the flexibility needed to manage the growing variability in energy supply.

Conventional power systems are dominated by dispatchable electricity generation units, based on fossil fuels, nuclear or hydropower. The electricity generated can be regulated easily in response to demand fluctuation. However, as the system is increasingly dominated by VRE, balancing becomes more challenging. Therefore, greater levels of flexibility will be required, which can be met through a suitable combination of the enabling strategies discussed here.

3.1.1 Infrastructure for flexibility

This subsection offers a brief overview of the key components of grid infrastructure that can enhance flexibility in power systems. It addresses the need for short-term flexibility, related to hourly variability within a day, as well as long-term flexibility, associated with seasonal and interannual variability. Subsequent sections will cover efforts to enable flexibility not directly related to grid infrastructure such as demand-side management, digitalisation and power-system specificities.

Grid modernisation and expansion

Adapting existing and new grid capacity to support new patterns and high variability in electricity flows is essential for a renewables-based energy transition. This involves making grids adaptable and resilient enough to accommodate fluctuations in electricity supply as power consumption continues to rise. Currently, investments to refurbish outdated grids and expand grid capacity are almost half of what is needed to meet the 2030 targets for renewable generation capacity, presenting a challenge for integrating VRE and ensuring energy supply.

Regions face these challenges in various contexts. For example, Europe and North America struggle to accommodate the current growth of renewables, having increased levels of curtailment, due to delayed acceleration of grid investments and aging infrastructure. Developing economies, such as those in sub-Saharan Africa, need to expand their grid infrastructure to meet increasing demands, but encounter difficulties in securing investments due to technical, regulatory and financial obstacles. The critical consequences of outdated infrastructure and insufficient investment in adequate grid expansion include grid congestion, which can result in curtailment, increased operational costs from underutilisation of least-cost generation resources and load shedding, potentially jeopardising energy security.

Modernising grids involves investments in grid-enhancing technologies, such as advanced sensors and power flow optimisation hardware and software tools, which are becoming increasingly important due to advancements in digitalisation. These technologies can also facilitate the integration of demand flexibility and storage solutions, expanding the range of flexibility options that can be employed to meet infrastructure needs. Implementing these measures is crucial for balancing supply and demand under varying conditions. In addition, non-technical measures must be considered to ensure adequate incentives for grid investments and efficient grid operation. These include regulatory reforms, improved permitting processes and enhancements in spatial planning.

Enhanced power system operations

In power systems with low shares of VRE, supply-side assets such as thermal generators with cycling capabilities (open-cycle gas turbines), along with flexible renewable sources such as hydropower and pumped hydro have historically provided the primary flexibility.[1] However, with the rapid growth of wind and solar energy in the power mix, it has become essential to expand the flexibility portfolio within the power sector to optimise the use of available resources. Innovative operational practices and incentives have already been implemented to unlock the inherent flexibility potential within power systems.

Balancing variable renewables on a system originally laid out under a different paradigm

The challenges to integrating solar and wind are primarily system specific, depending on factors such as system size, the availability of interconnectors, and the adequacy of regulations and incentives (Nordström *et al.*, 2023). Power systems are also evolving due to new technologies such as energy storage, market regulations and the increased demand for distributed generation and demand-side management. This shift necessitates new operational practices and closer co-operation between distribution and transmission operators (IRENA, 2019a).

1 IRENA (2018), Power System Flexibility for the Energy Transition, Part 1: Overview for policy makers, International Renewable Energy Agency, Abu Dhabi.

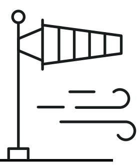
The variability of wind and solar generation poses operational challenges for power systems, which require enhanced system flexibility and innovative reserve requirements for capacity, real-time balancing and frequency control. Moreover, advanced tools and models are being developed to improve the forecasting of renewable energy generation. These forecasting models utilise advanced mathematical algorithms, high-resolution weather forecasts and machine learning, significantly increasing accuracy. Such enhancements allow forecasts to be generated at sub-hourly intervals, thereby reducing uncertainty for system operators and project owners when participating in the market.

In cases where transmission networks face congestion, solutions like utilising storage facilities to accommodate electricity at any given moment can be employed. Besides, dynamic line ratings can be applied to calculate the available capacity of transmission lines in real time taking into account factors like temperature and wind direction, maximising the utilisation of transmission capacity. With this, the maximum amount of power that is allowed to flow through a transmission line can be increased, compared with traditional methods which rely on fixed maximum capacities based on conservative assumptions for weather conditions.

Expanding balancing areas through enhanced interconnections

There is often a geographical mismatch between the best locations for renewable energy and the main demand centres, necessitating the transmission of electricity over long distances. Research on the spatial granularity of a market aims to identify such constraints across different bidding zones while providing efficient locational signals. These arrangements incentivise generation where it is most needed, while also promoting transmission investments in the appropriate locations.

The ability to trade electricity between countries can contribute to balancing supply and demand in large-size power systems. Balancing of variable power generation across extensive areas where renewable resource availability is heterogeneous can be enabled through interconnectivity, minimising curtailments and storage needs (Mai *et al.*, 2022). Interconnectors also foster synergies in providing services, such as operational reserves, and enable flexibility across borders (IRENA, 2023b). Additionally, the economic benefits of cross-border integration include greater cost-efficiency in energy system operation, which enhances the bankability of large renewable power generation projects, ultimately catering to the interests of multiple nations.



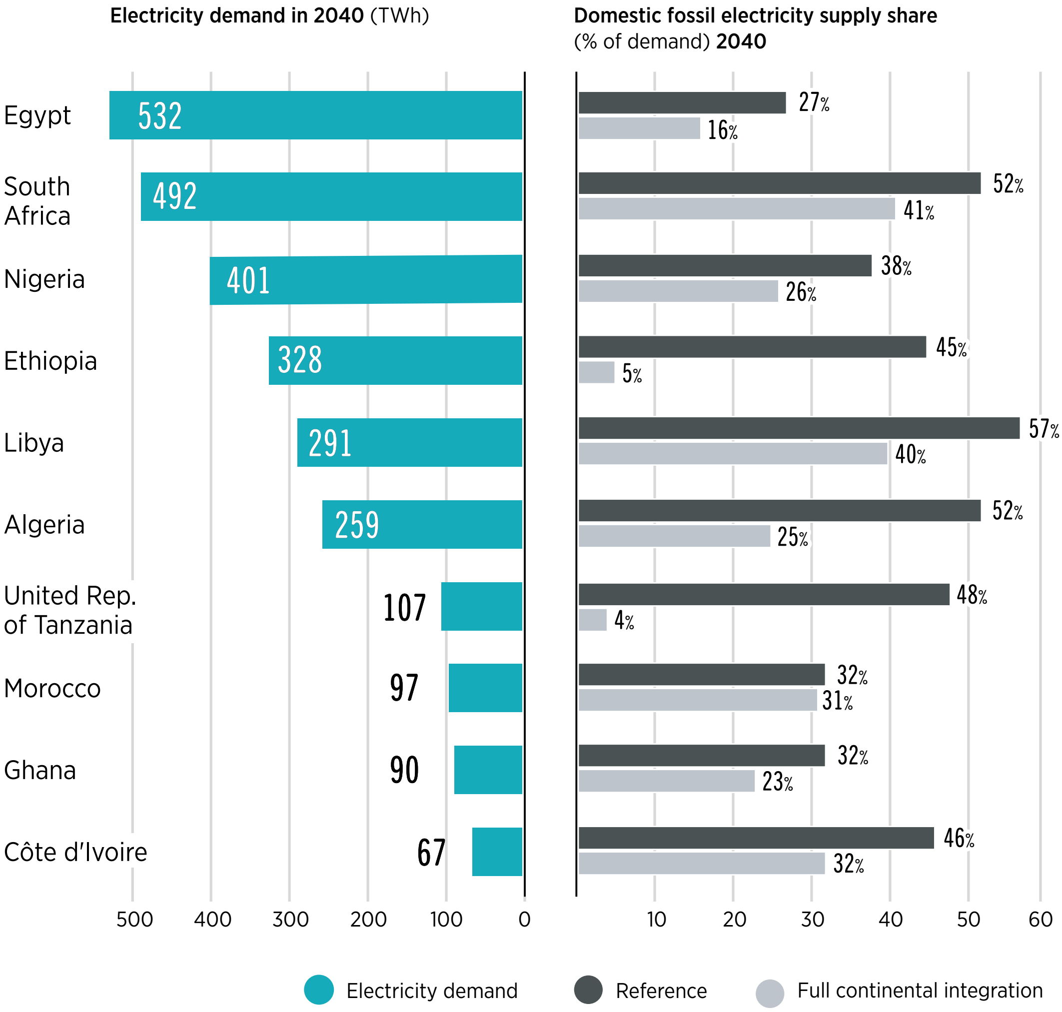
IRENA's latest *Renewable energy outlook for ASEAN: Towards a regional energy transition* indicates that hydropower-based countries in Southeast Asia like the Lao People's Democratic Republic and Myanmar can utilise their existing reservoirs to balance renewable energy generation across the region. During the day, hydropower units in these countries can reduce generation to accommodate imported solar electricity from nations such as Viet Nam, while maintaining water levels that would otherwise be used for energy production, thus enabling the export of electricity back to the regional grid at night. Leveraging the existing reservoirs in Lao PDR and Myanmar could be cost-effective, reducing the need for investment in storage alongside solar generation sources in Viet Nam. This example highlights the importance of regional planning that holistically considers all system assets across the region. A similar mechanism has been observed in Europe, Norway's hydro-based system supports Denmark, which often experiences wind generation exceeding demand at various times of the day.

Furthermore, a recent capacity expansion analysis conducted under the African Continental Power Systems Master Plan[2] (AUDA-NEPAD, 2023) indicates that by 2040, increasing cross-border electricity interconnections across Africa could potentially double the recommended uptake of new run-of-river hydropower capacity in the Democratic Republic of Congo, particularly linked to the site of Inga Falls upstream of the Congo River. Although, the Inga hydropower potential may not attract significant investment interest at the national level due to the country's relatively low energy needs, it becomes increasingly appealing at a regional level. If adequate infrastructure is developed, neighbouring countries could gain access to green and affordable electricity resources. Consequently, establishing cross-border interconnections across Africa could be crucial in generating international and interregional interest, and pooling capital resources for substantial infrastructure development at the Inga hydropower site.

A major cost saving arises from reductions in fuel consumption due to improved conditions for renewable energy integration. For instance, according to (AUDA-NEPAD, 2023), a continentally interconnected African power system would result in a significant displacement of fossil electricity use by 36% by 2040 (Figure 3.1). This shift would lead to equivalent reductions in emissions and fuel costs. Decreased reliance on fossil fuels not only lower costs for consumers but also strengthens national economies and reduces vulnerability to financial risks stemming from fluctuations in fuel prices.

2 An initiative of the African Union Development Agency (AUDA-NEPAD) supported by IRENA as the official modelling partner.

FIGURE 3.1 **In addition to minimising power system costs, integrating electricity systems across Africa could unlock further decarbonisation of electricity supply**



Note: The diagram shows significant reductions in domestic fossil fuel supply in Africa's ten highest annual demand countries by 2040, according to the Africa CMP scenarios (AUDA-NEPAD, 2023). Through increased interconnections of national grids across the continent, Africa is expected to see a significant drop of 36% in fossil electricity use (from 1 339 TWh in the reference scenario to 853 TWh in the full continental integration scenario). About 96% of the displaced fossil energy would originate from these countries, which together account for 80% of the continent's electricity demand (3 281 TWh). TWh = terawatt hour.

In a cost-optimal scheme for operating a VRE-rich interconnected system, complex cross-border energy flows of a bi-directional and multilateral nature are typically involved. Markets operating at the power-pool level support VRE by harnessing a region's spatiotemporal synergies which are complementary dynamics between renewable energy sources and demand profiles. Examples of some existing regional energy trading frameworks include the Southern African Power Pool (SAPP), the Central American Electrical Interconnection System (SIEPAC) and Nord Pool (Europe). These frameworks share a common objective: to gain economic and security benefits from the diversity of supply and demand, which ultimately lowers the climate impact of energy system operations. Generally, the full potential of regional interconnectors will require large-scale transmission interconnectors and adapted operation of various power plants on the technical side, open markets and the alignment of regulations and procedures among system operators to ensure reliable and efficient system functionality on the policy side (IRENA and AfDB, 2022).

Incorporating energy storage to enhance system flexibility

Energy storage, in its various forms and time scales, helps address the flexibility challenge by allowing surplus energy to be stored during periods of excess generation and utilised when needed. This decouples the moment of energy consumption from production, whether electrical or thermal. Storage can provide a variety of services to assist in the integration of solar and wind energy (IRENA, 2020a).

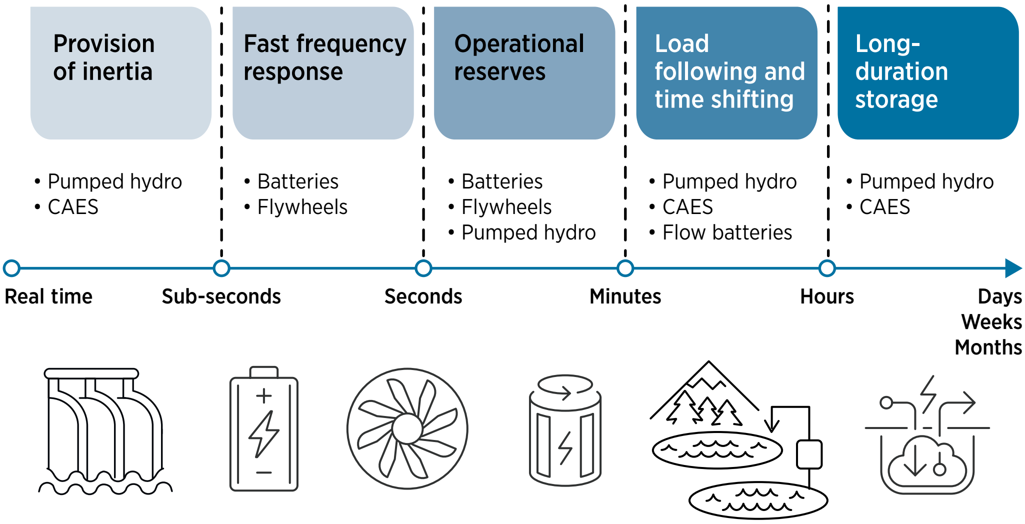
If permitted to participate in the electricity market, storage can store or release electricity in response to price signals. It can also alleviate the burden on congested transmission lines, making more efficient use of grid assets. Additionally, electricity storage can participate in capacity and ancillary services markets, providing grid services that have typically been met by conventional technologies. A key advantage of storage is its ability to offer multiple services simultaneously.

Several storage technologies with varying costs and technical suitability for providing specific services have emerged and are currently at different stages of maturity and deployment. For instance, batteries are well suited for responding almost instantaneously, making them capable of meeting services such as operating reserves. Conversely, if the aim is to shift the consumption of large volumes of electricity over extended periods – whether hours, days or even weeks – pumped hydropower is better placed. Overall, services can be classified based on the lead time required after a call from the system operator, or in terms of the storage duration during which the facility can discharge at full power after being fully charged (Figure 3.2).

Energy storage is classified into two categories based on storage capacity: short-term energy storage (STES) and long-duration energy storage (LDES). STES technologies provide continuous energy supply on a millisecond to an hourly scale, typically for durations of less than ten hours, while LDES technologies offer energy provision for longer periods exceeding ten hours. For example, battery storage is the predominant option for STES, whereas pumped hydro is currently the most common form of storage for LDES.

A combination of short-term and long-duration storage is essential to ensure the flexibility required for energy reliability and resilience in the future. The proportion of each type of storage should be tailored to the specific characteristics of each country's or region's power system.

FIGURE 3.2 **Storage technologies suitability to storage time**



Source: (IRENA, 2020a).
Note: CAES = compressed-air energy storage.

Short-duration energy storage (SDES) to maintain system stability and supply and demand balance

Typically, SDES can discharge at full power for up to 8-10 hours. It encompasses technologies that can instantly increase power output, thereby supporting system stability and balancing supply and demand across various time frames. In power systems dominated by solar and wind sources, where natural factors significantly influence the timing of electricity generation, the need for mechanisms to maintain this balance becomes increasingly critical.

SDES technologies are generally classified into four main categories: electrochemical (batteries), thermal (rocks, bricks or molten salts), mechanical (compressed air, liquid air or gravitational potential) and chemical (hydrogen or its derivatives). Among these, batteries are the most promising and widely adopted storage technology, capable of supporting frequent power ramping through charging and discharging. This widespread deployment has been driven by technological innovations and notable cost reductions.

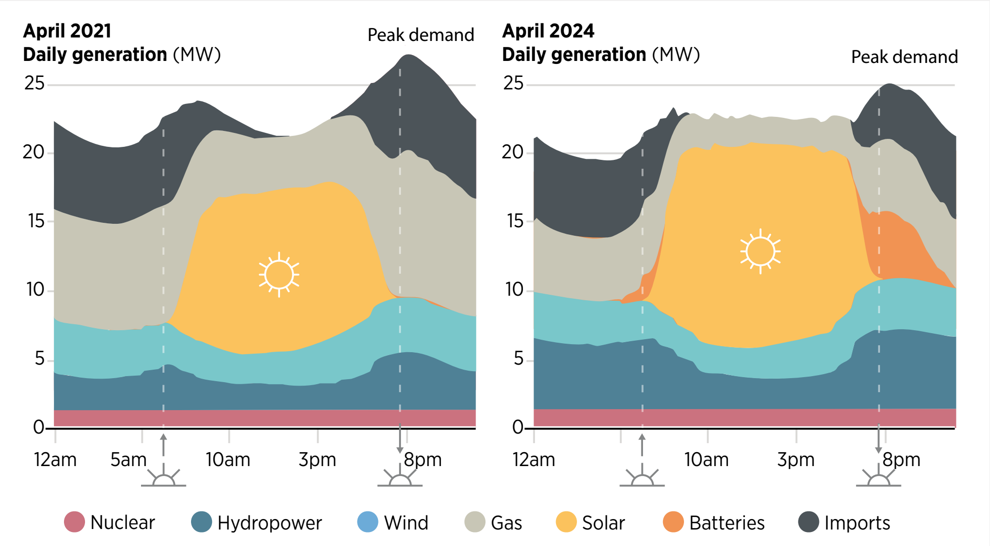
BOX 3.1 Investments in the energy-transition-related supply chain

Improvements in battery technology can also benefit other sectors that rely on stationary applications.

In the past two years, the global installed capacity of energy storage systems has doubled, reflecting the growth of electric vehicle batteries. Innovations in stationary batteries are focused on improving cost, durability and storage duration, with charging time being a less crucial factor. Annual battery storage demand for stationary applications is projected to rise from the current 120 gigawatt hours (GWh)/year to around 1 TWh/year (RMI 2023). Consequently, battery production capacity is expanding significantly – for every gigawatt of solar manufacturing capacity around 8 GWh of battery manufacturing capacity is expected to be available by the end of the present decade.[3] This growth is a result of a burgeoning battery market that is flattening the duck's curve.[4]

Figure 3.3 depicts the power dispatch for California on the same day in 2021 and 2024, indicating that the deployment of battery capacity has not only increased the amount of solar production the system can accommodate but also reduced peak demand during the evening. Energy stored in batteries during periods of high solar generation and low demand (and consequently low electricity prices) is released during high-demand periods, when electricity prices are high. This illustrates one of the key business cases for batteries, among other possibilities (IRENA, 2020a). The deployment of batteries also alleviates stress on grid infrastructure and displaces natural gas peaking plants, leading to significant reductions in emissions.

FIGURE 3.3 **California power dispatch in April 2021 (left) and April 2024 (right)**



Source: (Plumer and Popovich, 2024).

3 RMI (2024). The Cleantech Revolution It's exponential, disruptive, and now https://rmi.org/wp-content/uploads/dlm_uploads/2024/06/RMI-Cleantech-Revolution-pdf.pdf.

4 The duck curve is a graph of power production over the course of a day that shows the timing imbalance between peak demand and solar power generation.

Long duration energy storage to maintain system adequacy

System adequacy refers to the reliability margin of a power system, enabling it to cope with varying conditions, including extreme weather events, and to meet established standards. In a global energy landscape with an increasing shares of renewables, there may be instances where little or no energy can be generated from solar and wind sources during extended periods of cloudy days and/or extremely weak winds, lasting from several days to weeks. This situation could pose significant challenges to flexibility and reliability, which future power systems must be prepared to address, even if the likelihood of such occurrences is considered low. It is a crucial aspect of energy security.

LDES technologies, such as pumped storage, have been deployed for decades and could significantly support the system as the share of VRE approaches 70-80% of the total. Chemical LDES, such as hydrogen storage in salt caverns, has the potential to store energy for weeks to months and may play an important role in the future, although its development is still in the early stages. Additionally, compressed air energy storage, which is also dependent on geological underground conditions, shows promising prospects for the future. However, challenges remain, including geographical limitations, permitting issues and the absence of a supportive regulatory framework.

3.1.2 Demand-side management and sector coupling

Demand-side flexibility refers to the ability to adjust electricity consumption patterns in response to changes in energy system requirements. It encompasses a portion of demand, including that arising from the electrification of other energy sectors (*i.e.* heat or transport via sector coupling), which can be reduced, increased or shifted during specific periods. Demand-side flexibility is becoming increasingly important to transform and adapt how electricity is generated, transmitted, and consumed in the rapidly evolving landscape of the energy transition. In a context of higher shares of cost-competitive renewable electricity and growing energy demand, end-use sectors leverage this flexibility by substituting fossil fuels with electricity or electricity-derived energy carriers, such as green hydrogen, when technically feasible.

Traditionally, meeting consumers' electricity needs and maintaining the balance between demand and supply has focused on the supply side, particularly on generation, transmission and distribution infrastructure. However, as electricity demand steadily increases, there is a growing consensus that investing in infrastructure to meet this demand is not always necessary. Demand-side flexibility can defer (and sometimes avoid) some of these investments.

Demand-side flexibility offers numerous benefits, including reducing peak load, facilitating the integration of VRE sources into power systems and minimising electricity costs by shifting load to periods of lower supply prices. To fully realise the potential of demand-side flexibility, technological innovations such as smart meters, advanced energy management systems and Internet of Things (IoT)-enabled devices are essential, complemented by supportive policy frameworks such as time-of-use pricing and demand response incentives.

Sector coupling, essentially, expands demand-side management options, thereby providing the enhanced flexibility that energy systems require.

Through approaches such as electrification and thermal energy storage, various end-use sectors can be coupled to provide services such as heating, cooling and transport. Achieving this efficiently will require support from digital technologies and smart energy management systems, advanced weather forecasting tools for solar and wind generation, and innovative business models such as energy-as-a-service, aggregation, peer-to-peer electricity trading, community ownership models, pay-as-you-go and urban energy planning (IRENA, 2019a; IRENA, 2019b).

Coupling can also occur between energy carriers on the supply side, for instance, through power-to-gas. Both approaches are vital for making the future energy system more integrated and flexible, which is crucial for scaling up the integration of variable renewable sources.

In essence, coupling different sectors, supported by intelligent energy management systems, can expand the options for dispatching electricity generated from VRE sources enhancing grid flexibility. This, in turn, facilitates a greater share of renewables in the energy mix, leading to reductions in energy-related carbon emissions.

With growing shares of renewable electricity in the power generation mix, sector coupling presents clear advantages for cost-effective decarbonisation in end-use sectors such as transport, industry and buildings. It provides a crucial source of flexibility particularly when high percentages of electricity generation come from solar PV and wind power. Achieving this flexibility requires effective co-ordination across the power and other end-use sectors in terms of technological advancements, infrastructure development, regulations and market design.

Co-ordinated cross-sector technology development would enable end-use sectors to leverage the scaling up of renewable electricity generation while also ensuring reliable power system operations through enhanced grid flexibility. To improve system cost-efficiency and optimise the performance of integrated systems, the co-ordination of cross-sector infrastructure planning must be reinforced at both institutional and technical levels.

For instance, in the decarbonisation of hard-to-abate industrial subsectors such as iron and steel, shipping and aviation, co-ordinated planning can facilitate the integration of zero-carbon energy infrastructure – such as production and transportation of green hydrogen – into sector-specific net-zero decarbonisation strategies.

Demand-side flexibility: The case of mobility

Decarbonising mobility is a significant step towards a green energy transition. In the 1.5°C Scenario, the number of electric cars is expected to reach 360 million by 2023 and 2 180 million by 2050. IRENA estimates that electricity's share of total final energy consumption in the transport sector will rise to 7% by 2030 and 52% by 2050. This will require major investments in charging infrastructure, with a cumulative investment of USD 9 trillion required by 2050 (IRENA, 2022f, 2023b, 2023f).

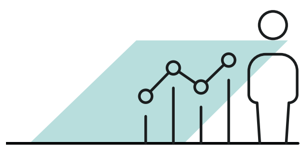
Smart charging refers to the adaptation of electric vehicle (EVs) charging cycles to align with both the conditions of the power system and the needs of vehicle users. Intelligent algorithms optimise the charging process by considering multiple factors, including electricity prices, the availability of renewable energy generation, local congestion and battery aging. Smart charging can be unidirectional (V1G) or bidirectional (V2G). While both systems require advanced digital infrastructure for energy management and data collection, bidirectional charging also requires V2G technology, allowing EVs to intelligently exchange energy with the grid (IRENA 2019c).

Cumulative charging patterns of EVs demonstrate highly random characteristics influenced by many factors. Consequently, maintaining the balance between supply and demand under these circumstances poses a challenge. Inadequate planning of power systems can lead to oversized cost-ineffective infrastructure. Thus, smart charging strategies for EVs can play a critical role in creating a flexible and efficient power infrastructure.

Smart electrification of end-use sectors

Smart electrification represents a cost-effective pathway to decarbonising energy systems by electrifying energy end-use sectors while unlocking flexible ways to consume electricity. There are two routes to electrifying end-use sectors: direct electrification, which involves technologies that convert electricity directly into useful energy, and indirect electrification, which refers to converting electricity into an intermediate energy vector that can later be transformed into useful energy. The production of green hydrogen, for instance, is expected to play a significant role in hard-to-abate sectors and may also serve as a storage medium. Either way, green electrification encompasses three major end-use sectors: transport, buildings and industries, which collectively account for three-quarters of global energy-related greenhouse gas emissions.[5] Demand-side flexibility can be fostered through smart appliances in buildings, industrial demand response and sector coupling. Sector coupling encompasses power-to-heat, power-to-gas (hydrogen) and power-to-mobility (smart EV charging) (IRENA, 2023f).

Smart electrification enables 1) power systems to accommodate new loads in a cost-efficient manner and creates 2) flexibility within power systems, allowing for the integration of a larger share of renewable energy sources, making power systems more robust and resilient. For end uses, electrification is 3) the most cost-effective solution for decarbonising these sectors. For consumers, it encourages active participation in the energy landscape by empowering them to define their own consumption strategies, such as reducing consumption during peak demand periods, shifting electricity use to off-peak hours and adjusting consumption in response to price signals.



5 https://www.iea.org/energy-system/.

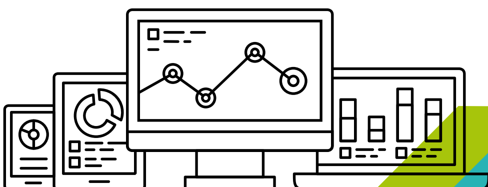
3.1.3 Digitalisation

Given the increased complexity of power system operations, digital solutions applied to power infrastructure are essential for adapting systems to new and challenging conditions. Recent advances in digitalisation allow infrastructure to cater to the unique characteristics of each system and address their flexibility needs. On the supply side, power generation is becoming more variable and decentralised, while on the demand side, new electricity-based end-use technologies, such as EVs and heat pumps, create higher and more dynamic loads. These new developments on both ends of the power system lead to new energy flow patterns, necessitating improved monitoring, management and control of power transmission and distribution to minimise faults and outages, thereby reducing monetary losses.

Digitalisation involves processing large volumes of data to add value to the power sector; the use of digital solutions in this field is not new. Converting data into value is a widespread practice, applied for monitoring and control at various levels of the power system, from generation to transmission, distribution and consumption. However, new advancements and increased capabilities for processing extensive data sets are creating opportunities to expand and enhance potential applications.

New services, such as improved performance monitoring, near-real-time operation and control, and enhanced forecasting, facilitate quicker system responses and better predictability. These services can be integrated into the system through the adoption of smart meters and sensors, the use of IoT, artificial intelligence and blockchain. These new and improved services become increasingly important as the flexibility requirements of the power system grow, playing a crucial role in reducing the costs of integrating VRE. Currently, smart devices that direct solar generation to daytime loads and facilitate overnight storage are already adopted in households. For instance, they store rooftop solar-PV generation instead of injecting it into the grid, run electric heat pumps and operate smart appliances. Other applications, such as battery management systems and smart charging of EVs, are gaining traction, although cost reductions are necessary for wide-scale implementation.

Digitalisation is a vital enabler of the energy transition, and its applications in power infrastructure play a key role in facilitating the tripling of power capacity by 2030. It enhances the operation, co-ordination and integration of various stakeholders in the system, ranging from generators and investors to end consumers, across diverse system configurations, particularly in distributed and decentralised energy systems. Consequently, while broadening its applications opens up opportunities for improved market designs and business models, it also requires appropriate financial and regulatory environments.



3.1.4 Power system specificity

The configuration of a power system is directly influenced by the environmental and social factors surrounding it. Each power system is characterised by varying electricity generation mixes, which depend on resource availability and existing interconnection levels, as well as demand profiles shaped by socio-economic aspects such as demographics and income levels. The decarbonisation strategies of different countries and regions require tailored approaches to transform their power sectors, with flexibility being one of the most critical considerations.

While it is essential to consider all sources of flexibility holistically, it is equally vital to recognise that flexibility solutions are highly system specific. Consequently, the value of flexibility varies depending on the specific flexibility source and the system in which it is applied. For instance, countries with higher solar PV generation require flexibility solutions to manage the day-night variation in supply, whereas those dominated by wind power must address seasonal fluctuations. The level of interconnection will also lead to distinct flexibility approaches because bulk electricity trade necessitates different control and monitoring measures compared to smaller-scale decentralised trade. Similarly, countries with large water reservoirs may adopt different flexibility solutions – potentially, less reliant on LDES – than those without such implicit energy storage capabilities.

To effectively leverage the most suitable flexibility solution for a country, system characteristics and energy transition plans must align with the available flexibility options. IRENA conducted a sensitivity analysis to examine the positive impact of different flexibility enablers on power systems in 2050 under the 1.5°C Scenario. Its key findings include:[6]

- Australia is poised to be one of the leading exporters of green hydrogen, while India, with its substantial hydrogen demand expected to be met domestically, has implemented significant capacities of electrolysers within its power systems. This highlights the importance of leveraging flexibility through electrolyser operations in both countries.
- In countries like Brazil and India, advanced non-conventional forms of LDES appear less relevant due to the adequate seasonal flexibility provided by large hydro reservoirs.
- As for Continental Europe and Great Britain, the options for flexible generation (such as hydropower) and long-duration storage may be limited. However, demand-side solutions such as heat pumps, flexible industrial loads and smart electric vehicle charging seem more relevant, especially when combined with battery storage.
- Despite being capital intensive and geographically restricted at times, pumped hydro storage is significant in Asian countries, particularly those with limited interconnection options, such as the Republic of Korea and Japan. Similarly, battery storage may be more crucial for countries with restricted interconnection options, as it allows for short-term storage and ramping services.

Similar insights have been identified in previous flexibility assessments conducted by IRENA across various countries and regions, highlighting that different flexibility enablers have varying impacts on the respective power systems.[7]

Providing flexibility within a system is essential for the energy transition, and many solutions and enablers can be utilised to meet this need. It is important to plan strategically and conduct focused technical and techno-economic studies to determine the most effective combination of available flexibility options.

6 This analysis should be regarded as indicative since not all flexibility solutions are examined concurrently, and insights may vary significantly when considering all sources simultaneously.

7 For more information see: www.irena.org/Energy-Transition/Planning/Flextool

3.2 Key technical barriers and enablers for 100% renewable power systems

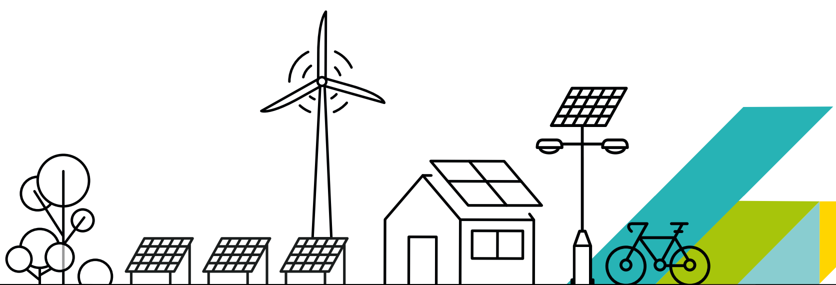
The provision of energy exclusively from renewable resources has been the subject of research for almost 50 years. Interest in this topic has surged since the last decade (Khalili and Breyer, 2022). In recent years, an increasing number of local and regional governments as well as countries have set 100% renewable energy targets, particularly in the electricity sector (IRENA Coalition for Action, 2019). Major players in the corporate sector are also supporting 100% renewable energy initiatives, which are vital for energy transformation as it catalyses investments in renewable sources (IRENA Coalition for Action, 2019).

There has also been a notable increase in research works and authors proposing scenarios that achieve 100% renewable energy over the past decade (Khalili *et al.*, 2022). In most of the recently proposed scenarios, electrification and sector coupling are identified as critical components. For example, in the 100% renewable scenarios assessed in (IRENA Coalition for Action, 2024), the share of electricity in total final energy consumption by 2050 is projected to be between 50% and 90%, in contrast to around 22% today.

Given the relevance of electrification and sector coupling, power systems that reliably and efficiently supply all of their electricity needs from renewable sources are essential for achieving 100% renewable energy systems. In the context of this report, power systems with a 100% renewable energy supply are defined as those that meet electricity demand solely through renewable sources, 24 hours a day, every day of the year.[8]

Achieving 100% renewable electricity supply is feasible but challenging in the current technological landscape. Addressing the operational challenges that arise when reaching this 100% threshold and deploying the most suitable solutions require further research and development.

While it is technically possible for any power system to produce 100% of its electricity from renewable energy sources, the key challenge is to ensure that this supply meets the demand in a resilient, reliable and economically viable manner. This depends on various factors, including the system's load size and geographical scope, the mix of renewable resources, the adequacy of transmission and distribution networks, the levels of interconnectivity, the availability of diverse energy storage solutions and the flexibility of the demand.



8 This definition excludes low-emission and carbon capture technologies that are addressed in other decarbonisation scenarios.

3.2.1 Defining the boundaries of the power system to set 100% renewable energy targets

When establishing national or regional targets for 100% renewable energy, power systems are typically defined by country or regional borders. This approach overlooks business entities, corporations or cities that might achieve a 100% renewable energy supply through renewable energy credits or other financial mechanisms (Denholm *et al.*, 2021), yet still operate within a national or regional power system where not all electricity originates from renewable sources.

Country- or regional-level power systems can be interconnected, creating larger zones, such as the Continental Europe Synchronous Area, the Nordic Synchronous Area (which includes Norway, Sweden, Finland and the eastern part of Denmark), or the Eastern and Western Interconnections in the United States. These interconnected areas have the potential to enhance system strength and stability. With favourable regulatory conditions that allow for co-ordinated operations, these areas can take advantage of shared flexibility resources and a more diverse energy mix, which facilitates the integration of higher proportions of renewable energy.

Power systems embedded within a larger interconnected area can more easily leverage the system's strength and flexibility to achieve 100% renewable energy shares, compared to isolated power systems. These interconnected systems benefit from comparative advantages such as greater resource and load diversity, the availability of more flexibility resources and enhanced stability. However, as all power systems within an interconnected area strive towards 100% renewables, challenges will inevitably arise, despite these advantages.

By the end of 2021, several countries and sub-national regions, including Costa Rica, Denmark, Norway, Iceland, Uruguay, South Australia, parts of Hawaii (United States) and Quebec (Canada), had consistently met their electricity demands entirely with renewable energy for extended periods (REN21, 2022). Some of these power systems benefit from robust interconnections with larger grids that provide dispatchable generation, enabling the export and import of power as needed. Others rely on a diverse mix of local renewable sources along with substantial dispatchable capacity. For example, Costa Rica's power system operates at nearly 100% renewable energy annually. In 2017, it functioned entirely on renewables for over 330 days, with the energy mix primarily composed of hydro power (77%), geothermal (12%) and wind (10%), with about 1% from non-renewable sources (Government of Costa Rica, 2017). Similarly, Iceland consistently meets its electricity demands through dispatchable hydro and geothermal resources.

There are several examples of small, isolated power systems, including microgrids and mini-grids, that are entirely powered by renewable energy resources supplemented with batteries. In many instances, the investments required to maintain the reliability of these systems are financially viable, offering returns through savings in fuel and operational costs. According to analyses by IRENA, various small island developing states could fully meet their electricity demand by renewables at a feasible cost, for instance, in Palau (IRENA, 2022c).

3.2.2 Large power systems: VRE vs dispatchable resources for 100% renewable energy supply

The changes necessary to transition to a 100% renewable power supply at large country or regional scales will vary depending on the unique characteristics of each power system. The type and diversity of available renewable power resources play a crucial role in this transition.

The output of VRE plants is influenced by local weather conditions, leading to intra-day, seasonal and interannual variability as well as forecast uncertainties. This results in limited capability to continuously match real-time demand. In contrast, the power output from non-variable or dispatchable renewables can be controlled and accurately predicted, better aligning with power system operations and planning schedules. For example, despite being subject to seasonal and extreme weather variations, hydropower with large reservoirs presents less uncertainty regarding resource availability over longer time horizons compared to VRE.

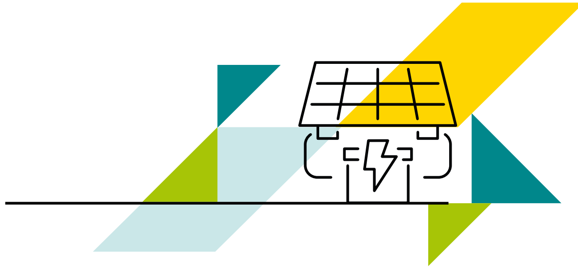
Power systems supplied by dispatchable renewables will share similar characteristics with current power systems, in crucial areas related to reliability such as voltage control, protection and stability. Conversely, a system that is dominated or solely supplied by inverter-based generation, such as VRE [9] resources, will exhibit different behaviours that may not align with current practices and infrastructure.

In power systems with a 100% renewable energy supply that predominantly relies on VRE, where substantial portions of the system or interconnected area operate exclusively with inverter-based generation, new infrastructure measures and control techniques – currently under investigation – will need to be implemented to ensure a stable and reliable electricity supply.

While striving for 100% renewable energy, maintaining a continuous and reliable energy supply can be less challenging in power systems with abundant dispatchable renewable resources than in those reliant on VRE. However, affordable dispatchable renewable resources are not widely available worldwide. In contrast, the broader distribution and lower costs associated with VRE make them a more likely source for future bulk electricity generation.

Achieving 100% levels based on VRE will require additional measures and may necessitate the adoption of new technologies that have not yet been deployed on a large scale. The efforts needed to implement these changes must be weighed against the benefits of completing the final transition from net-zero emission scenarios to a fully renewable energy supply.

9 In inverter-based generation, such as solar and wind power, the energy sources connect to the grid via power electronic inverters. By contrast, in conventional generation, including most dispatchable renewables like hydro or geothermal, the energy sources connect to the grid through conventional synchronous generators.



3.2.3 The challenges and way forward for achieving 100% renewables based on VRE

Given the nature of VRE, two primary techno-economic challenges have been identified in the literature for establishing a reliable and economically viable electricity supply solely from renewables, especially when VRE is predominant (Denholm *et al.*, 2021; Mai *et al.*, 2022):

- Economically balancing supply and demand across all time scales, from short-term fluctuations to seasonal and extreme weather events.
- Adapting power grids to ensure reliable and stable operation with a predominance of inverter-based generation.

Balancing supply and demand across all time scales

The primary objective of power system operations is to match supply and demand at the lowest possible cost, considering daily and seasonal consumption patterns. Traditionally, continuously running power plants, known as base load generation, have supplied most of the electricity needed. Peaking power plants are then deployed to meet additional demand during peak hours or specific seasons and to serve as backups during emergencies.

As the power sector transitions, VRE resources are beginning to take on some of the roles traditionally held by base load generation, providing large volumes of electricity at a low cost. In theory, VRE could supply all the electricity required in a power system. However, due to their reliance on weather conditions, VREs often struggle to consistently meet demand without additional measures. Transitioning to a fully renewable electricity supply based solely on VRE would require significant over-installation of VRE, resulting in extremely high levels of curtailment and a dramatic increase in electricity costs. Therefore, strategic deployment of complementary flexibility solutions is essential.

The implementation of flexibility measures discussed in previous chapters – primarily enhanced power system operation practices, increased use of interconnections and short-duration battery energy storage – has enabled the efficient integration of annual VRE shares ranging from 30% to 50% in various countries.[10] Beyond these shares, studies suggest that there is a breaking point, which varies depending on the characteristics of each power system. For instance, in the cases studied by (Denholm *et al.*, 2021; Mai *et al.*, 2022), this point was identified as approximately 92%-94%, beyond which current flexibility enablers may be insufficient to achieve the 100% target at an economically viable cost.

10 More than 50% in specific cases such as Denmark.

Additional solutions that are not yet fully deployed, such as long-duration storage, active multi-day demand participation and further exploration of options for clean peaking-dispatchable renewable power plants[11] may be necessary to maintain a cost-effective balance across all time scales, from seconds to seasons and longer climate cycles.

The precise combination of new flexibility measures, their associated costs, the business models needed for their implementation, and the threshold at which largely unimplemented solutions would become effective, still remain subjects of investigation. These factors depend on the specific characteristics of each power system.

Reliable and stable operation of inverter-dominated power grids

The design of the control schemes for voltage and frequency, the principles governing the design and operation of the protection schemes,[12] and the procedures for recovering from major disturbances, are all fundamental to the reliable operation of a power system. These designs have traditionally relied on the physical characteristics of conventional synchronous generation.[13] In contrast, VRE resources typically connect to the grid, using power electronic inverters, resulting in a different physical response to disturbances compared to conventional synchronous generation.

As the proportion of inverter-based generation increases, it gradually displaces conventional synchronous generation in the operation of power systems. This transition alters the system's response to disturbances, potentially undermining the effectiveness of established control and protection schemes, thereby jeopardising the stability and reliability of power system operations (Breithaupt *et al.*, 2016).

To ensure system stability, particularly in large country or regional interconnected grids, the penetration levels of inverter-based generation are currently limited to thresholds identified through detailed engineering studies. An exception exists in small, isolated grids, where it has been possible to operate solely with inverter-based generation and batteries using grid-forming inverter technology.

The adoption of technologies that have not yet been fully deployed or standardised in large power systems such as grid-forming inverters for connecting solar and wind resources to the grid,[14] alongside more mature technologies like synchronous condensers and FACTS (Flexible Alternating Current Transmission System), as well as new advanced monitoring and control practices by system operators – all supported by digitalisation – can facilitate the transition to stable operation of large power systems with reduced or even no synchronous generation.

The level of VRE shares that necessitate the deployment of new technologies, as well as the optimal strategies for their implementation, must be determined based on detailed technical studies tailored to the characteristics of each power system. The costs, efforts and business models required for this transition will also vary according to the unique characteristics of each power system or interconnected area.

11 For example, thermal plants powered by hydrogen or biofuels.

12 Protection schemes guarantee the safety of people and infrastructure by automatically disconnecting equipment or parts of the power system in the event of a failure.

13 Such as thermal or hydro power plants.

14 Grid-forming inverters respond to disturbances similarly to conventional generation, in contrast to the currently deployed solar and wind inverter-based generation technology, known as grid-following inverters.

3.3 Creating an enabling framework for greater power sector flexibility and electrification

Although a variety of technical solutions are available to accommodate high levels of renewables, including VRE, policy makers and regulators need to address several barriers to their deployment. These include outdated power sector structures with marginal pricing that fails to incentivise adequate renewable capacity, insufficient storage options, higher costs compared to incumbent technologies in end-use sectors (*e.g.* heat pumps versus gas boilers or EVs versus combustion engines, as well as the high and uncertain costs of green hydrogen. A lack of investor confidence stemming from policy uncertainty further complicates this situation.

Policy makers can address these barriers first and foremost through clear targets and strategies. Possible implementation options include updating electricity market structures and rules to foster an enabling environment for increased system flexibility, enacting policies to accelerate end-use electrification and creating incentives for indirect electrification, specifically through green hydrogen.

Setting clear targets and strategies

In addition to setting ambitious targets for renewable power aligned with the tripling target and a 1.5°C pathway, establishing specific storage targets is crucial for both the short term (by 2030, linked to the tripling) and the long term, to advocate long-duration storage solutions. Such solutions include pumped storage, which has particularly lengthy project lead times, as well as early-stage technologies that need time to scale and drive down costs (IRENA *et al.*, 2024).

As noted in Chapter 3.1.4, power system specificity underlines the need for national assessment of the generation mix and all flexibility resources, in order to define effective and efficient targets for deployment of storage and grids. General guidance ranges from 1-2 MW of energy storage per each 10 MW of renewable power capacity added, while the needed characteristics, as duration, and specific sizing will depend on availability of the multiple and diverse flexibility resources mentioned. In a similar way, although reinforcement of grids is an urgent need to avoid bottlenecks in the renewable flows, proactiveness is the only blueprint and expansion must be tailored to national needs. An early assessment of these needs and the inclusion of its outcome in the NDC and national energy strategies can notably support the timely achievement of the decarbonisation targets.

For green hydrogen, whose costs remain significantly higher than conventional methods, a comprehensive green hydrogen strategy, developed and endorsed by the government, can help boost investor confidence. Such a strategy would not only signal the government's commitment to a sustainable energy future, but also strengthen the business case for industry pioneers (IRENA, 2024c).

Power sector restructuring, including procurement of flexibility options

Specific procurement mechanisms must be established to secure the necessary generation and ancillary services at a low cost, as current market arrangements increasingly fail to meet the needs of an energy system with a high share of renewables. One option is the dual procurement mechanism outlined in (IRENA, 2022d). This mechanism aims to procure renewable electricity or long-term storage solutions through long-term contracts (*e.g.* via auctions) at low capital costs. This approach minimises the cost of renewable power generation while facilitating capacity expansion. Simultaneously, a short-term flexibility market would operate on marginal prices to acquire the flexible resources essential for a reliable renewables-based power system.

Policies to promote end-use electrification

End-use electrification has been gathering pace, but as noted in Chapter 2, it is not at the required pace. Sales of heat pumps and EVs have even declined in some countries. Therefore, governments must continue to promote these electrification options through a range of policies and incentives such as mandates for heat pumps in new buildings, targets for phasing out combustion engines and support mechanisms like EV subsidies.

Specific measures are also necessary to encourage "smart" electrification. For example, smart charging systems are crucial for preventing adverse impacts on power grids and leveraging the potential grid flexibility services that EVs can offer. Policy makers should therefore consider implementing smart charging policies similar to those adopted in the United Kingdom (mandating Open Charge Point Protocol compliance from 2022), as well as in Belgium and Luxembourg (IRENA, 2023b).

Policies aimed at promoting/incentivising indirect electrification

Green hydrogen plays a vital role as both a flexibility option and a means for decarbonising hard-to-abate sectors, such as heavy industry. However, green hydrogen continues to face numerous obstacles, including technological, economic, institutional and social challenges. Aside from high and uncertain costs, these barriers include a lack of certainty about off-takers, poor co-ordination between national authorities, and the challenges and costs associated with hydrogen transport.

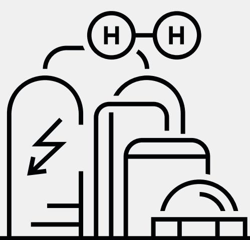
While no single instrument can address all the barriers to scaling up green hydrogen, auctions have emerged as a promising option. They have proven instrumental in reducing the costs of renewable power deployment (see Box 3.2) (IRENA, 2024d). Green hydrogen auctions can be designed to help achieve the policy objectives outlined in the national green hydrogen strategy.

BOX 3.2 Auctions for green hydrogen

Competitive public procurement – or auctions – is emerging as a tool to promote the production and use of green hydrogen. Like all tariff-based support schemes, auctions offer long-term revenue certainty to facilitate long-term budgetary planning, and the ability to progress along on the technology learning curve. In addition, the competitive nature of auctions allows for true price discovery, revealing a feasible remuneration for producers and the willingness to pay from consumers, thereby minimising the overall cost of public support. Auctions also create a clear pipeline of future projects, enhance transparency in project selection and the level of support received, ensure timely delivery of bid promises, and can be designed to achieve broader policy objectives for green hydrogen deployment or to address specific barriers.

Auctions can be conducted domestically, where off-takers and producers are within the same country as seen in India; regionally, where they operate within the same bloc such as the European Hydrogen Bank auction; or internationally, where off-takers and producers span designated countries, as in the H2Global auction. One option is supply-side auctions where competition occurs among hydrogen producers, aiming to scale up electrolyser capacity and the production of green hydrogen (or its derivates). A recent report by IRENA (2024d) indicates that such auctions are particularly suitable in regions with strong potential for renewable energy sources and effective logistical capabilities. They can reflect the set targets in a straightforward way.

Hydrogen auctions can be tailored to achieve specific objectives. If the primary aim is to decarbonise economies at the lowest price, countries or jurisdictions might consider design elements that focus on minimising costs of support, such as adopting technology-neutral auctions that prioritise the lowest-price technologies, using winner selection criteria based solely on price and introducing a ceiling price above which bids would not be accepted. However, such approaches could be less supportive of local value chain development and may be more suited to countries such as Germany, Japan and the Republic of Korea, which are likely to prioritise imports over domestic production.



Countries or jurisdictions aiming to decarbonise while enhancing energy security through local green hydrogen production (*e.g.* China, India) may consider scheduling auctions to attract investments in upstream activities. These auctions should focus on developing specific technologies and include criteria for winner selection and qualification requirements that emphasise local content. Additionally, provisions to prevent market concentration could encourage new entrants and promote liquidity in the hydrogen market.

Countries or jurisdictions with abundant renewable energy, land and water resources seeking to engage in international hydrogen trade (*e.g.* Morocco) might design elements that promote competitive pricing while fostering innovation and industrial development. These design elements include denominating contracts in hard currency or incorporating indexation clauses to account for inflation.

Source: reproduced from (IRENA, 2024d).

CHAPTER 04

OVERCOMING FINANCE AND INVESTMENT BARRIERS AND MEETING ENERGY TRANSITION SKILLS REQUIREMENTS

KEY POINTS

- A just and inclusive global energy transition will require a massive scale-up of finance in countries that have otherwise received limited investments in the energy sector. Although global investments are on an uptrend, most of this growth is concentrated in a few advanced economies, leading to widening disparities in investment levels.
- Policies and measures must be implemented to tackle the high costs associated with capital in emerging and developing economies, making projects bankable and enabling greater investment flows. This will require co-ordinated efforts among governments, international donors, multilateral development banks and the private sector.
- In contexts where existing interventions may fail to render projects bankable, public financing and policy must work together to shift the focus from bankability to impact potential. Investment decisions should consider factors beyond financial returns for private investors; they should encompass both short- and long-term climate, environmental, socio-economic and developmental goals including paving the way for the next generation of renewable energy projects, while producing numerous socio-economic benefits. Such financing should also avoid exacerbating domestic debt burdens.
- Philanthropic capital is uniquely positioned to fund “unbankable” projects and contexts, as it is meant to be driven by impact. However, the current involvement of philanthropic organisations in the energy transition remains limited in scale, geography and scope. Moving forward, philanthropies could play a more substantial role in financing energy-transition-related projects in “high-risk” contexts.

4.1 The geographic concentration of investments[1]

Advanced economies – 38 countries that make up 14% of the world's population and represent 40% of global GDP – accounted for USD 800 billion in energy transition investments, which is 47% of the global total (Figure 4.1). The United States and the European Union (EU) have led these investments, recently bolstered by the expansionary fiscal stimulus for clean energy sectors initiated by the US Inflation Reduction Act and the EU's Green Deal. These policies are anticipated to continue driving energy transition investments in the years ahead.

Emerging markets and developing economies (EMDEs, or the Global South)[2] received 53% (just under USD 900 billion) of global investments, with the majority directed towards China, India and Brazil. These three countries represent 38% of the world's population and 27% of its GDP, collectively accounting for nearly 43% of global investment (Figure 4.1).

In contrast, half of the world's population – comprising more than 150 economies outside China, India and Brazil and representing one-third of global GDP – received only 10% of the energy transition investments (Figure 4.1). This small share of funding is primarily concentrated in key EMDE markets including Viet Nam, Poland, Mexico, Chile, Indonesia, the United Arab Emirates, Thailand, the Philippines, the Russian Federation, Malaysia, Hungary and Peru. The remaining 140 EMDEs received less than 7% of global investments.

4.2 Structural changes needed to close the financing gap

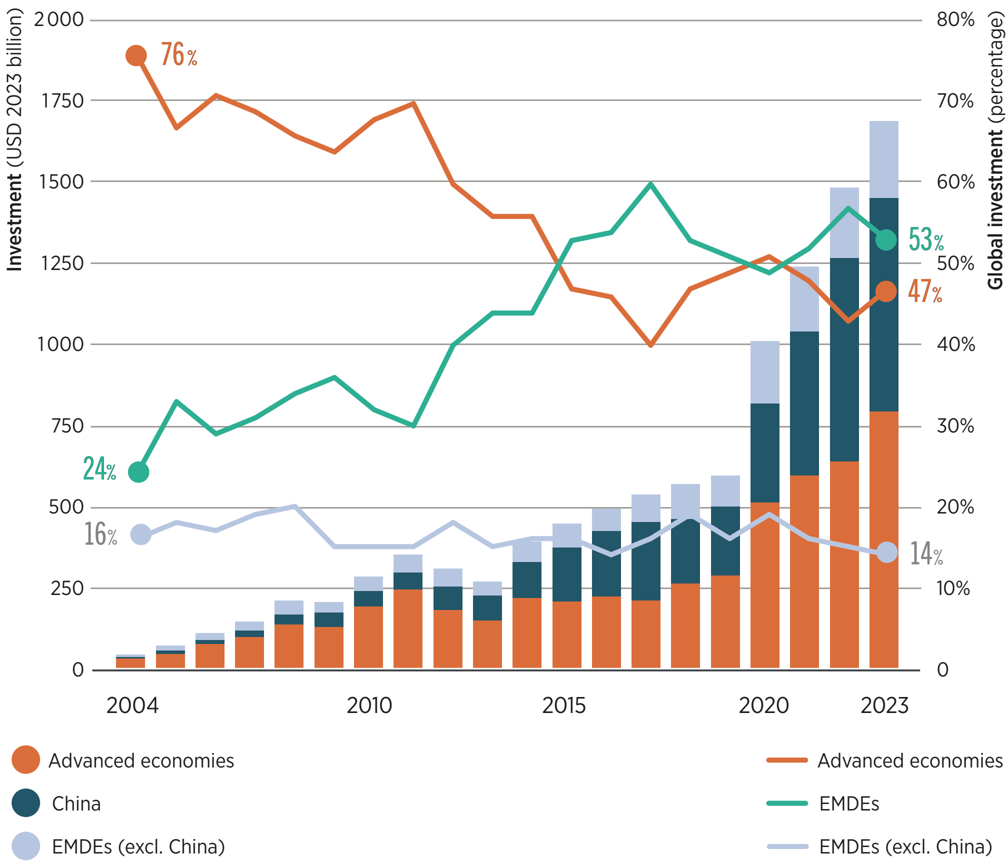
While enabling frameworks at the national level (*e.g.* policies and regulations) have a role to play, underlying structural challenges hinder infrastructure financing to flow into countries that need it the most. Given the current macro-economic environment, there is a pressing need to reconsider and adapt existing risk-driven frameworks that guide the flow of development capital and public financing into emerging economies. Public financing plays a crucial role that goes well beyond merely de-risking private capital; it is also essential for bridging the gaps in areas where private capital is currently lacking.

To effect this change, public financing and policy de-risking must be co-ordinated to shift the focus from bankability to the potential for impact. Investment decisions should consider factors beyond the immediate

1 Global investments in energy transition-related technologies – excluding energy efficiency – reached a record high of USD 1.7 trillion in 2023 (BNEF, 2024c). Transition-related investments (including energy efficiency) exceeded USD 2 trillion in 2023. However, energy efficiency data from (IEA, n.d.) are not disaggregated by country. Consequently, the remainder of this section will concentrate on transition-related investments excluding energy efficiency to facilitate analysis in relation to EMDEs. For electricity grids, clean hydrogen and renewable power, data from (BNEF, 2024a) were utilised as they gave a detailed country breakdown. This differs from the data presented in section 2.3, although the country breakdown is expected to be quite similar.

2 The group of EMDEs comprises 155 countries, according to the International Monetary Fund (IMF, 2023b).

FIGURE 4.1 Energy transition-related investments in advanced economies and emerging and developing economies



Based on: (BNEF, 2024a).

Notes: Excludes investments in energy efficiency due to lack of country-level data. For the same reason, data source for electricity grids, clean hydrogen, and renewable power is different from that presented in section 2.4.

financial returns for private investors, including both short- and long-term climate, environmental, socio-economic and developmental goals, alongside the project's potential to stimulate the renewable energy sector. IRENA is currently developing an expanded framework to measure impact potential, enabling projects with significant benefits for community welfare to secure financing even if they do not meet conventional bankability criteria. In this new framework, welfare encompasses energy access and affordability; socio-economic development in terms of productive uses, jobs and income; and market creation potential by serving as first-mover pilots.

To finance projects with high impact potential, public funds must be disbursed as direct investments, grants, rebates and subsidies. For instance, grants can establish funds that leverage risk mitigation instruments without further straining the budgets of already indebted countries. Currently, the most commonly used instruments are loans, which are typically offered at market rates. In markets perceived as high risk these rates are the highest, meaning the poorest populations are paying the most for (often basic) energy. Therefore, there is a pressing need to rethink the way risks are defined, shifting from a narrow focus on investors' concerns about renewable energy investments not paying off to a broader view encompassing the risks of leaving people behind, failing to meet climate goals and neglecting half of the world's population.

Public investments are also needed for developing ecosystems around training, education and local industry development, as well as implementing policies that ensure the transition benefits the local economy. Since these falls outside the remit of the private sector, and given that the domestic public sector is financially stressed in many developing countries today, international collaboration will be essential.

For EMDEs facing energy access deficits, particularly least-developed countries, whose escalating debt burdens and constrained fiscal space hamper their ability to realise their development priorities, international flows of public finance, predominantly from G20 members, are essential (UNCTAD, 2023). To this end, international financial institutions, including multilateral development banks and climate and development funds, can play a pivotal role in ensuring universal energy access, alleviating poverty, and achieving sustainable development and climate goals.

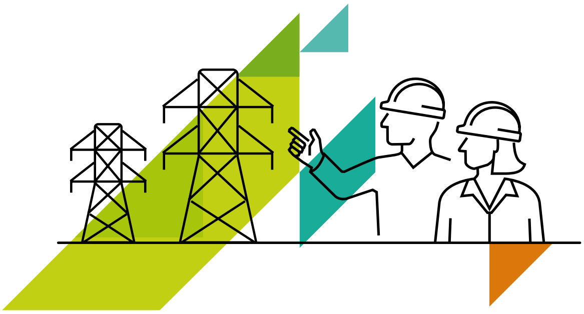
Several initiatives are now calling for a revamp of the international financing architecture. Notably, the Bridgetown Initiative urges global leaders to provide emergency liquidity and rethink the terms governing loans and repayments to developing countries. There are also calls to expand multilateral lending to governments by USD 1 trillion to tackle systemic challenges at the heart of the current crises.

And finally, as the discourse on just and inclusive energy transitions gains momentum, we must redefine the climate narrative and clarify what a just transition means in terms of equity, social justice and the restoration of natural systems (see Chapter 4). Important steps are already being taken in this direction through initiatives, such as the Just Energy Transition Partnership, which mobilise international co-operation and support to facilitate the energy transition in developing countries. However, their generally narrow focus on smoothing the "phaseout of conventional sectors" and use of non-grant instruments (*e.g.* loans, debt) needs to expand to include "value creation from emerging sectors" (*e.g.* critical minerals) and grant mechanisms (*e.g.* subsidies, results-based financing) to ensure a more equitable distribution of the benefits derived from the energy transition. Such holistic and just transition programmes will need to transcend energy policy silos and interact closely with policies and institutions related to industry, education and training, among others (*e.g.* the US Inflation Reduction Act). International co-operation must be oriented towards this new approach to local value creation.

4.3 International collaboration as a conduit for financing

International financial collaboration, involving the flow of funds from the Global North to the Global South, is crucial for tackling the current socio-economic gaps produced by inadequate socio-economic structures, thereby creating the space for structural changes while simultaneously addressing the unfolding climate crisis. The necessary international finance flows represent a significant effort that cannot be sustained indefinitely. Therefore, it is vital that transition narratives and roadmaps address the required changes in socio-economic structures from the outset. This need for structural change includes climate finance itself, which in its current form may exacerbate global injustice through the pursuit of profit, or green extractivism (Dafermos, 2023).

When seeking to find or replenish funds, the international community can explore various avenues, including channelling philanthropic funds, revenues from carbon pricing or implementing a more progressive tax system. This section primarily addresses philanthropic funds, while carbon price and wealth taxation will be discussed in Chapter 5. With an estimated USD 811 billion in philanthropic donations directed towards development causes in 2022 alone (Desanlis *et al.*, 2023), charitable trusts and individual donors can play a vital role in mobilising private funding for the energy transition. Philanthropies are uniquely positioned to finance projects that are often considered unbankable, or simply do not have enough access to finance, ranging from initiatives requiring just a few thousand dollars up to multi-million dollar, multi-year projects. Consequently, philanthropy can fill critical funding gaps and address needs that might not be met by governments or traditional investment sources. This flexibility allows philanthropic funds to be deployed in ways that maximise their impact.



The urgent need for climate mitigation and adaptation to safeguard livelihoods, especially in developing countries, closely aligns renewable energy and SDG7-related projects with the missions of numerous philanthropic funds, both large and small. These missions include fighting poverty, combating environmental destruction and air pollution, promoting access to effective health care and education, and fostering community building, equity and social justice. An increasing number of global philanthropic now explicitly incorporate climate action into their core fund missions, although references to clean, renewable energy often remain more ambiguous.[3]

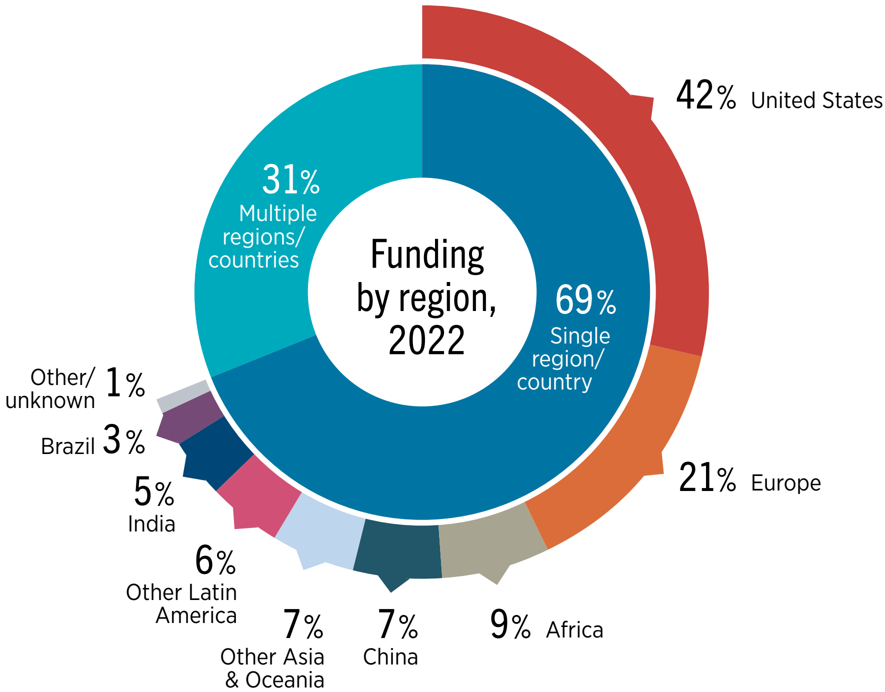
Despite the significant potential for philanthropic funding to positively influence climate mitigation worldwide, global philanthropic funding for climate-related activities remains surprisingly low compared to other areas of philanthropic work. Climateworks (2023) estimates that out of the total USD 811 billion philanthropic funding in 2022, only USD 7.8 billion to USD 12.8 billion – less than 2% of the total – was focused on climate change mitigation. Of this limited amount, only about USD 260 million was directed towards clean energy, which is a disappointing fraction of the total. This shortfall is particularly concerning given the urgent need for climate action and the essential role that sustainable energy access plays in the mission objectives of many philanthropic funds. Climateworks also highlights that overall philanthropic giving in 2022 remained essentially unchanged compared with 2021, as did funding for climate change mitigation, despite previous years witnessing significant increases from much lower levels (Desanlis *et al.*, 2023, 2022).

Philanthropic funding for climate mitigation includes a wide range of fields, which can be consolidated into four main areas: enabling environment, sustainable energy, cross-sectoral initiatives and land use (Desanlis *et al.*, 2023). Among these, the enabling environment – encompassing public engagement, governance, capacity-building and sustainable finance – receives the largest share of funding, followed by sustainable energy. Within the sub-categories, clean energy attracted the most philanthropic funding for climate mitigation in 2022, amounting to USD 260 million, followed by public engagement at USD 255 million (Desanlis *et al.*, 2023).

Climate philanthropy is not only limited in scope, but also in terms of geography. In 2022, 30% of overall foundation funding for climate change mitigation was allocated to initiatives spanning multiple regions (Figure 4.2). Meanwhile, more than 60% of funding directed to a single country or region was concentrated in the United States, Canada and Europe alone (Desanlis *et al.*, 2023). By contrast, Africa, which hosts some of the world's most vulnerable populations to climate change (IPCC, 2022), received only 6% of total foundation funding for climate change mitigation – or 9% of funding directed to a single country or region – in 2022 (Desanlis *et al.*, 2023). Although funding for climate mitigation in Africa has more than tripled over the last five years, it started at a very low baseline (Ibid) and remains a fraction of what is needed.

3 This is based on IRENA's analysis of the mission statements of 25 of the world's largest philanthropic funds, ranked by total financial endowment.

FIGURE 4.2 Known foundation funding to climate change mitigation by region



Source: (Desanlis *et al.*, 2023).

Philanthropy has the potential to significantly impact climate mitigation, particularly in financing renewable energy projects worldwide. In 2023, a coalition of leading climate philanthropies announced a three-year commitment of USD 450 million to accelerate the phasedown of methane and other non-CO_2 super climate pollutants (Candid, 2023). More such commitments are essential, specifically targeting the deployment of renewable energy solutions that encounter substantial financing challenges, ranging from large- to small-scale projects to microfinance.

Aside from the materialisation of finance flows, the distribution of these funds is crucial for achieving a just and equitable transition. This topic is further explored in Chapter 5.

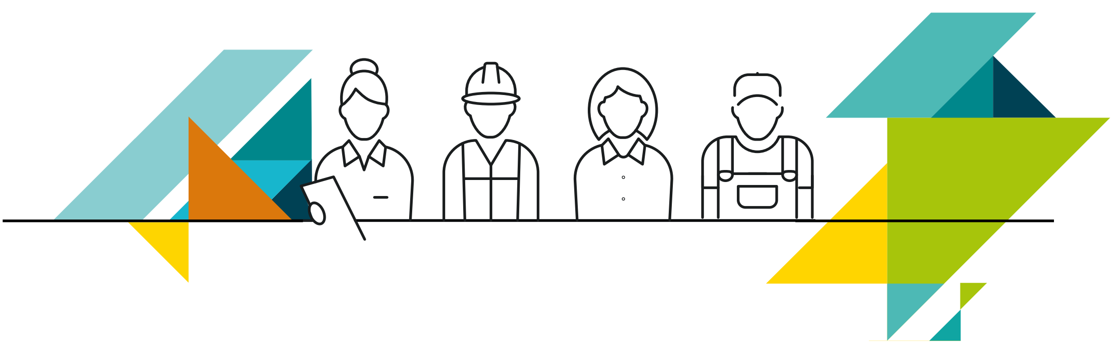
For the financial flows to maximise social value, countries must implement appropriate policies and governance. There is a strong feedback loop between these two elements: insufficient financial flows do not create opportunities for significant social value creation or for an engaging transition narrative. However, a lack of effective governance and policies to direct finance flows towards meaningful social value creation disincentivises the necessary level of funding.

4.4 Ensuring the right skills for the transition

The economic development pathway pursued by countries will have implications for job creation and skills requirements across the entire value chain. This includes areas such as infrastructure, manufacturing capacities, development, operation and maintenance as well as the mining, processing and recycling of critical materials. To achieve energy transition goals, it is essential to invest in building the associated labour and professional workforce and addressing skills shortages. The *World Energy Transitions Outlook* identifies skilling as one of its main pillars. Many countries and industries are already experiencing acute skills shortages, a gap that is likely to widen as nations strive to meet ambitious targets, such as the goal to triple renewable power capacity. Therefore, urgent action is needed to scale up education and training efforts to address current and future human capital needs. Education- and skills-related policies and measures must be tailored to the diverse circumstances of different countries and regions, considering the specific pathways they are taking and the associated implications for employment including priority technologies and sectors, anticipated job creation numbers, occupational patterns and geographical/spatial distribution along the value chain.

As countries seek to strengthen their industrial base and build manufacturing capacity, skilling in this area will become increasingly important. Developing robust supply chains and ensuring that the resultant benefits are shared equitably among countries, particularly emerging markets and developing economies, will be crucial for delivering a just and inclusive energy transition. In addition to addressing constraints arising from a lack of skilled labour, the need for local value creation and regional supply chain investment must be carefully balanced with the reduction of trade barriers for goods and services vital to the renewables industry. This balance will be key to preventing the intensification of supply chain bottlenecks and ensuring that renewables remain cost competitive as a trade-off for maximising socio-economic benefits. Adopting more complex production systems and advancing up the value chain, including the development of local and regional manufacturing hubs, will require investment in skilling a modern manufacturing workforce, incorporating a strengthening of related science, technology, engineering and mathematics (STEM) education as well as advanced manufacturing skill sets.

More broadly, energy transition measures must prioritise education and training to build a representative and skilled workforce that utilises the talents of individuals from all backgrounds. This involves strengthening the integration of essential renewable-energy-related knowledge and skills across various learning provisions, including technical and vocational education and training, higher education, micro-credentials and targeted training as well as workplace learning (such as apprenticeships). Integration of transition skills into existing programmes and disciplines and creation of new targeted programmes must be pursued in collaboration with employers to ensure that the curricula align with industry needs. The capacity of educators, trainers and instructors must be enhanced to ensure that their teaching practices reflect the emerging advancements and requirements of the sector.



Alongside training a new generation of energy professionals, reskilling, upskilling and professional development will be vital in equipping the existing workforce to meet emerging skill demands. Workforce reorientation will be particularly important for reskilling fossil fuel workers. Mapping transferable skills will be a key step in mitigating the unemployment risks associated with transitioning from fossil-fuel-intensive industries to renewable energy. Fortunately, analyses of skill requirements underscore many synergies, such as those between the offshore wind and oil and gas industries. Transferable skills in this context include expertise in surveying and offshore installation; designing and manufacturing of support structures; and large-scale installation and operation and maintenance of offshore assets (IRENA and ILO, 2021) .

Developing national qualifications based on occupational standards for key renewable energy jobs is an important step in defining the knowledge, skills and competencies needed. Such standards should be developed and ratified by sectoral skills bodies or councils that include industry representatives, government officials and the education sector. Establishing a robust national qualification framework will ensure that the curriculum developed by education and training providers is sufficiently capable of meeting the skills needs for the transition. Accountability frameworks are necessary not only for the accreditation of education and training bodies but also for structuring examination and licensing procedures as well as processes for the review, update and adoption of new qualifications.

Regionally adopted qualification frameworks or standards can further support the movement of skilled workers between countries by facilitating compatible skill standards and mutual recognition of qualifications.

Close co-operation between government ministries (particularly those responsible for energy, education and labour), education and training providers, and industry is essential for developing strategies to address current and emerging skills shortages. These public-private partnerships are not only crucial for establishing skills and occupational standards, as previously discussed, but they also play a significant role in the design and delivery of courses as well as the transfer of equipment from industry to training institutions. Industry can further support workplace learning models to facilitate hands-on and experiential learning, including industry placements, internships and apprenticeship programmes. Financing education and training presents a key challenge. Increasingly, countries are establishing dedicated “transition training funds” to equip their citizens for the transition workforce, particularly in communities and regions affected by job losses. Public-private partnerships can also assist in the financing of education and training initiatives through mechanisms such as payroll training levies and tax incentives.

A key dimension of promoting a just and inclusive energy transition is ensuring that all individuals, especially those from marginalised and under-represented groups, can benefit from the opportunities created. Targeted education and training measures are essential for building an inclusive workforce that represents women, minorities, youth, people with disabilities, low-income persons and older workers. Beyond fostering equity, such diversification enables employers to tap into previously overlooked talent pools. These measures may include early exposure to renewable-energy-related topics and career opportunities, scholarships and funded training initiatives, mentorship schemes and targeted apprenticeship programmes. Additionally, energy education through basic schooling and lifelong learning is necessary to cultivate an empowered society equipped with the knowledge and values to demand and contribute to the transition.

CHAPTER 05

FURTHERING ECONOMIC AND SOCIAL DEVELOPMENT: **A JUST AND INCLUSIVE ENERGY TRANSITION**

KEY POINTS

- A key benefit of the energy transition is its potential to enhance overall global welfare, including social and environmental aspects. IRENA's analysis of the socio-economic dimension of the transition, extends beyond merely the technological dimension, recognising that this will be crucial for a successful and sustainable transition. The socio-economic dimension comprises three pillars – inclusive development, equity and justice – along with international collaboration as a cross-cutting component across the pillars.
- The findings indicate that even if a transition based on a 1.5°C Scenario were successfully implemented, significant disparities would persist globally, affecting both the Global North and Global South. Some remaining disparities are common between these regions, particularly in the distributional and social dimensions, although the gaps may be more pronounced in the Global South (especially in the social dimension).
- The current state of energy access highlights that the energy transition, as it stands, lacks inclusivity, equity and justice. In 2022, 685 million people lacked access to electricity, and 2.1 billion access to clean cooking and the SDG7 target on universal energy access looks increasingly likely to be missed. Nearly all the population without energy access resides in the Global South, with Sub-Saharan Africa accounting for 85% of the global access deficit.
- The technical and commercial solutions needed to achieve universal access to reliable and affordable electricity from sustainable power systems across the Global South are already available, alongside abundant renewable energy resources. Increasing access to existing technologies, fostering capacity building and providing affordable finance would empower the Global South to harness its renewable energy potential, thereby contributing to the global goals of universal energy access and net-zero emissions, while facilitating a just transition.
- Finance mobilised through international collaboration is essential for achieving a just and inclusive transition, particularly in relation to energy access and other welfare dimensions. However, reaching an international consensus on adequate financing has proved elusive in recent decades. Socio-economic analyses of the potential impacts of collaborative international financing have been lacking, yet they are crucial to produce insights that inform these discussions. IRENA has been addressing this gap by evaluating the socio-economic footprint impacts of various energy transition pathways in conjunction with different levels of collaborative international finance flows.

05

5.1 Socio-economic impacts of the 1.5°C Scenario

Developing energy transition roadmaps that consider broader socio-economic impacts is essential. Understanding a roadmap's implications for economic, social and political dynamics is also important. This knowledge helps anticipate and mitigate barriers, facilitating a smoother transition.

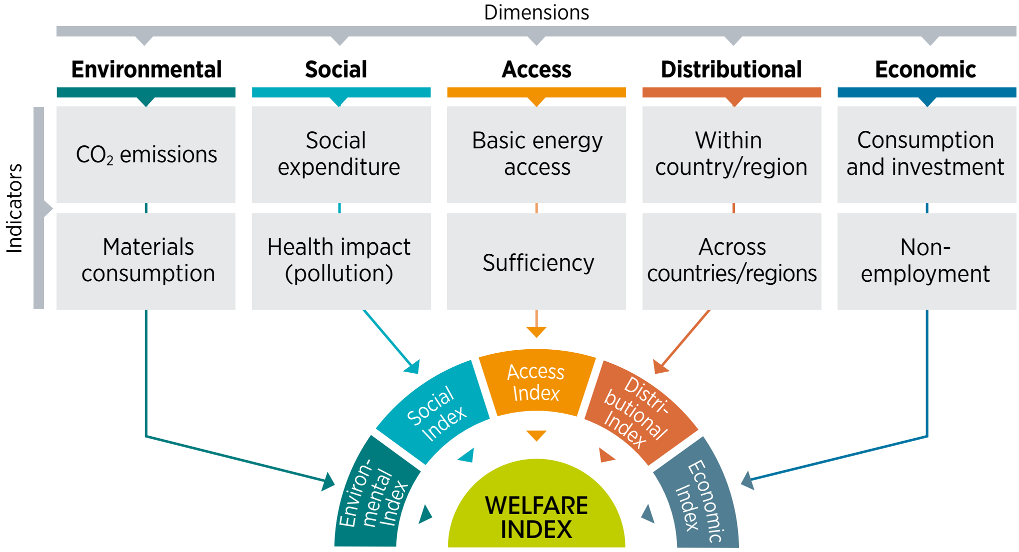
Since 2016, IRENA has been at the forefront of analysing the socio-economic impacts of the energy transition (IRENA, 2016) and has produced insights on the implications of energy transition roadmaps for economic and social systems at the global, regional and national levels (IRENA, 2017a, 2022e, 2023b, 2023c; IRENA and AfDB, 2022a).

In light of the unfolding crises affecting the global climate, biodiversity and inequality, there is an added urgency to the transition and the need for a resilient approach. If not properly managed, this urgency could exacerbate the negative socio-economic impacts of the energy transition. A failure to emphasise resilience may increase the vulnerability of much of the world's population, intensifying the impact of climate change and biodiversity loss, magnifying inequality and creating insurmountable barriers to transition. Maximising socio-economic benefits should therefore be a primary focus of those planning and implementing the energy transition.

IRENA's socio-economic footprint analysis examines the impact of the energy transition on aggregated economic activity, employment (across the economy, the energy sector and renewables) and welfare (IRENA, 2023b). Historically, most emissions originate from developed countries, while developing nations face challenges of limited social and physical infrastructure, making it difficult for them to adapt to climate change and enhance resilience. To evaluate the socio-economic footprint of transition roadmaps, IRENA employs an integrated modelling framework that links the world's energy systems with its economies. Previous editions of the World Energy Transitions Outlook (WETO) point out that transitioning to a 1.5°C Scenario would result in more job creation and improved human welfare compared to the Planned Energy Scenario (PES), assuming an appropriate policy framework is in place.

This chapter will focus on socio-economic gaps, primarily measured by IRENA's energy transition welfare index. This index is informed by five dimensional indices – environmental, social, access, distributional and economic – each of which consists of two indicators (Figure 5.1) (IRENA, 2016, 2017b, 2018, 2019b, 2020b, 2021, 2022f, 2023b).

FIGURE 5.1 IRENA's overall welfare index with its five dimensions (dimensional indices) and two indicators per dimension

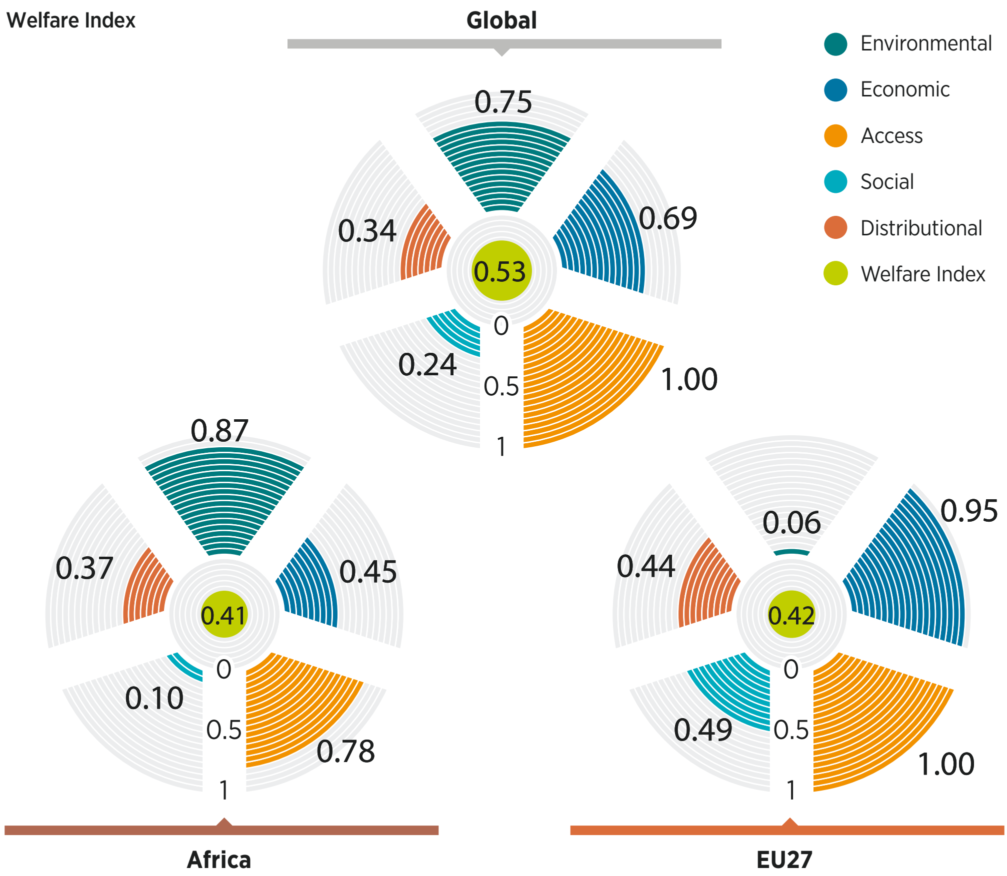


Source: (IRENA, 2023b)..
Note: CO_2= carbon dioxide.

Figure 5.2 illustrates the overall welfare index and its corresponding dimensional welfare indices for 2050 under IRENA's 1.5°C Scenario as presented in the latest WETO edition, for both the global context as well as for certain regions (*e.g.* Africa and the 27 member countries of the European Union [EU-27]) (IRENA, 2023b). The welfare index and its five dimensions are structured on a scale ranging from 0 (low performance) to 1 (high performance). Graphically, the overall welfare index may be depicted in a flower-shaped illustration, with the five-dimensional indices the "petals". The overall index values for Africa and the EU-27 are close, at 0.41 and 0.42, respectively, yet their performance varies across different dimensions. The EU-27 outperforms Africa in the economic, social and access dimensions, while Africa excels in the environmental dimension, despite its greater vulnerability to climate change, mainly due to its significantly lower material consumption (IRENA, 2023b). The welfare index and its dimensional indices show substantial improvement with the transition; without the transition, the welfare indices would be markedly worse by 2050, particularly under the PES.[1]

1 For additional details on welfare impacts associated with implementing IRENA's energy transition scenario, please refer to IRENA (2023b).

FIGURE 5.2 Overall welfare index and dimensional welfare indexes for the 1.5°C Scenario by 2050: Global, Africa and EU27



Source: (IRENA, 2023b).

Figure 5.2 clearly illustrates that even if an energy transition following IRENA's 1.5°C Scenario is successfully implemented, significant welfare gaps may exist from the energy perspective, in both the Global North and South. Some of these gaps would be in common, such as those in the distributional and social dimensions, although they may be more pronounced in the Global South (especially in the social dimension). The Global South also faces substantial gaps in the economic dimension, while the Global North continues to struggle with a significant gap in the environmental dimension, primarily due to high levels of material consumption driven by its high aggregated economic activity. These persistent welfare gaps can create societal and political barriers that may ultimately hinder the successful completion of the energy transition.

This chapter explores options to bridge these persistent welfare gaps, aiming to inform transition planning and policy making for a feasible and sustainable transition.

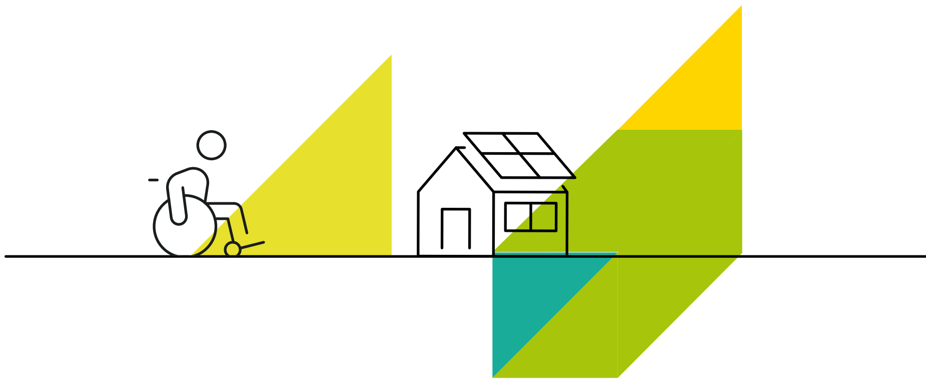
5.1.1 The socio-economic dimension of the transition

The systemic nature of the energy transition, characterised by the integration of the energy system within economic and social systems and the multiple feedback loops between these layers, has been extensively examined in various analyses (IRENA, 2019b, 2020b, 2021, 2022f, 2023b; IRENA *et al.*, 2022a). The energy system is not standalone: its purpose is to serve and provide value to economic and social systems. Therefore, adopting a holistic approach is key for energy transition planning and policy.

To date, there has been more emphasis on the technological aspects of the energy transition: specifically, replacing fossil fuel technologies with renewables and improving energy efficiency. The larger picture, meanwhile, encompasses economic, social and environmental dimensions and associated policy-making. The socio-economic layer comprises three pillars – inclusive development, equity and justice – with international collaboration acting as a transversal component across the three (Figure 5.3).

FIGURE 5.3 The socio-economic dimension of the transition with its three pillars (inclusive development, equity and justice) and international collaboration as a transversal element

Note: The inclusive development component stands for globally shared prosperity, providing space for inclusive development for all. Structural changes in the economy are a key component for opening up space for inclusive development within planetary boundaries (Brand *et al.*, 2021; Ensor, and Hoddy, 2021; Richardson *et al.*, 2023; Rockstrom *et al.*, 2023)



The inclusive development component represents a commitment to globally shared prosperity. Structural changes in the economy are essential for facilitating inclusive development within planetary boundaries[2] (Brand *et al.*, 2021; Ensor and Hoddy, 2021; Richardson *et al.*, 2023; Rockstrom *et al.*, 2023) and for limiting global warming so that it does not undermine development itself. The equity component focuses on how to fairly distribute the benefits and burdens stemming from the transition. It considers the distributional aspects of emissions, energy, income, wealth and economic opportunity, while acknowledging historical responsibilities. Furthermore, it aspires towards shared prosperity, ensuring that the transition processes do not perpetuate or exacerbate existing socio-economic disparities. The justice component means not leaving behind those who at present remain heavily dependent on fossil fuels, whether in terms of supply (*i.e.* producers) or demand (i.e. energy use patterns).

In this context, international collaboration involves providing access to finance on fair terms (section 5.2) and contributing to the structural changes necessary to bridge socio-economic gaps and disparities (section 5.3).

5.1.2 Advancing holistic energy transition narratives

Chapter 1 highlighted the important gap between current ambitions and the actions necessary to meet the 1.5°C climate target. Projected reductions are insufficient to close the emissions gap. Feedback across inter-connected systems – energy, economy, society and the Earth – suggests that unaddressed socio-economic disparities could severely impede the effective implementation of transition plans and strategies. Current events in many countries show that population groups that feel disadvantaged or neglected may mobilise to oppose transition efforts. This becomes critical in a context in which a much swifter transition becomes necessary to close the widening divide between existing transition planning and mitigation pathways aligned with remaining carbon budgets.

Transition narratives and scenarios that address equity, inclusivity and justice gaps upfront can help bring about the unprecedented global collaborative effort required to address current challenges. The next two sections of this chapter will discuss the role of international collaboration with the aim of maximising socio-economic benefits and exploring potential structural changes.

2 The latest scientific assessment of nine planetary boundaries reveals that six of them have already been surpassed. Alongside climate change, the boundaries of concern include biosphere integrity, land systems, freshwater, biogeochemical flows and novel entities. The remaining three boundaries pertain to ocean acidification, atmospheric aerosol loading and stratospheric ozone depletion (Richardson et al., 2023).

5.2 The role of collaborative international finance flows in the energy transition debate

Financial flows from the Global North to the Global South are vital to addressing long-standing socio-economic disparities and ongoing multi-crises.

For sustainability, collaborative international finance flows need to be adaptive during the transitional period. Their purpose is to address existing socio-economic gaps, enabling the necessary space for structural changes while simultaneously addressing the unfolding climate and biodiversity crisis. However, international consensus on how to realise this has proven elusive over the past decades.

Socio-economic quantifications of the impacts of collaborative international finance have been lacking, yet these are essential for producing insights that inform these discussions. IRENA has been addressing this issue by quantifying the socio-economic footprint impacts of various energy transition pathways that involve differing levels of international finance (IRENA, 2021, 2022f; IRENA and AfDB, 2022):[3]

5.2.1 Funding the energy transition

Over the years, various estimates have been made of the financial requirements for meeting the technological need of climate mitigation, the phaseout of fossil fuels, a just transition, loss and damages, climate adaptation and inclusive development.

In preparation for the 2021 United Nations Climate Change Conference (COP26), the Standing Committee on Finance operating under the United Nations Framework Convention on Climate Change (UNFCCC) produced its first report on the financial needs of developing-country parties in the implementation of the Convention and the Paris Agreement.[4] The report estimated that just over 40% of the needs from the Nationally Determined Contributions (NDCs) would cost approximately USD 6 trillion cumulatively by 2030, with about USD 0.5 trillion per year identified as requiring international sources of finance (UNFCCC Standing Committee on Finance, 2021). A report commissioned by the UK and Egyptian governments for the Independent High-Level Expert Group on Climate Finance, presented at the 2022 United Nations Climate Change Conference (COP27), quantified the climate finance needed in emerging markets and developing economies excluding China, as USD 2.4 trillion per year by 2030, with USD 1 trillion per year needing to come from external financing (Songwe *et al.*, 2022).

3 Collaborative international finance is understood here as grants and concessional finance, primarily consisting of non-debt-bearing financial support.

4 The Second Report is anticipated to be released in Q4 2024.

In another study (Bhattacharya *et al.*, 2022), the aggregate investment needs for emerging markets and developing economies in areas such as human capital, sustainable infrastructure and accelerated energy transition, adaptation and resilience, and the restoration of natural capital is estimated at USD 3.5 trillion per year by 2030. In contrast, Fanning and Hickel (2023) take a different approach by quantifying the equity pillar of the socio-economic dimension, excluding justice and inclusion considerations. They argue that during the transition to net zero by 2050, when considering historical and remaining emissions, some countries would exceed their equality-based share of the available carbon budget while others would emit less than their fair share: "the Global North would overshoot its collective equality-based share of the 1.5°C carbon budget by a factor of three, appropriating half of the Global South's share in the process". Using median marginal abatement costs derived from IPCC-AR6[5] mitigation pathways that aim to limit warming to 1.5°C with minimal or no overshoot, Fanning and Hickel quantify this imbalance as a requirement for compensation for atmospheric appropriation.[5] This compensation amounts to USD 192 trillion[6] cumulatively, translating to about USD 7.4 trillion[7] per year in annual payments that would need to flow from the Global North to the Global South if disbursed between 2024 and 2050. The authors also propose a methodology to allocate these financial flows among nations based on their carbon credits, measured by the balance between their cumulative emissions and their fair share.

At the 2015 Paris Climate Conference (COP21), a new collective, quantified goal (NCQG) for climate finance was set, starting at a minimum of USD 100 billion per year, taking into account the needs and priorities of developing countries prior to 2025. The NCQG will be established at the CMA[8] 6 session linked to the 2024 Baku Climate Conference (COP29). In February 2024, India's submission to the NCQG process stated, "In line with the needs of developing countries, developed countries need to provide at least USD 1 trillion per year, composed primarily of grants and concessional finance. With the availability of the updated Needs Determination Report, the quantum can be scaled up in proportion to the rise in the needs of developing countries" ('NCQG submission: India', 2024).

IRENA's analysis of the socio-economic footprint of the energy transition, explored in previous WETO editions and regional analyses,[9] indicated that financial flows from the Global North to the Global South could range at USD 0.3, 1, and 2 trillion[10] per year (IRENA, 2021, 2022f, 2023b; IRENA *et al.*, 2022a). This aligns well with the aforementioned needs. The results of these socio-economic assessments (presented in section 5.2.5) can inform current discussions on collaborative international finance.

5 This may be linked to the Loss and damages discussion, as these over-emissions contribute to climate-induced losses and damages.

6 In 2010 USD.

7 In 2010 USD.

8 The Conference of the Parties serves as the meeting of the Parties to the Paris Agreement.

9 Forthcoming IRENA reports will provide regional energy transition outlooks.

10 Unless otherwise noted, this and all currency figures that follow are in 2021 USD.

5.2.2 How to source collaborative international finance flows?

There are several ways to manage collaborative international finance. This section considers a public-private partnership approach.

The principle of Common but Differentiated Responsibilities and Respective Capabilities (CBDR-RC), as outlined by the UNFCCC, highlights the central role of equity in sourcing international finance, whether it be public or private. Although this principle was included in the 1992 treaty, it has failed to translate into significant financial flows. In the 2009 Copenhagen Accord (15th Conference of the Parties, COP15), later ratified in the 2010 Cancun Agreements, developed countries committed to mobilising USD 100 billion a year jointly by 2020 to meet the needs of developing countries. However, by 2021, only a small fraction of this target was met (Gabbatiss, 2021) (Carty *et al.*, 2020). Nevertheless, there are signs of a growing momentum towards international collaboration on financing, evident in milestones such as the first Just Energy Transition Partnership (COP26) and the establishment of a Loss and Damage Fund (COP27), which was operationalised at COP28 in 2023. The example of the climate damages tax (Sharma *et al.*, 2024) illustrates an attempt to introduce a carbon tax for fossil fuel producers, primarily designated for the UNFCCC Loss and Damages Fund. However, like other carbon taxes, it faces the challenge of anticipated regressive impacts and declining revenues as technological advancements progress. Additionally, Brazil's G20 presidency in 2024 is advocating for a co-ordinated international effort to improve wealth taxation ahead of COP30 in 2025.

The push for increased taxation of wealthy individuals is also gaining momentum because of its potential to significantly boost collaborative international finance while tackling inequality. This inequality represents an important gap in the socio-economic realm and directly contributes to the climate crisis, impacting socio-economic resilience against climate effects. Wealth inequality and concentration of wealth among the top tier of the distribution have risen substantially since the 1980s (Piketty, 2020). These trends have further intensified in recent years due to the COVID-19 pandemic and the energy crisis triggered by the war in Ukraine (Chancel *et al.*, 2022). The lack of effective progressive taxation and tax evasion practices among the wealthiest individuals have significantly contributed to the growth of wealth inequality, while reducing public fiscal resources (EUTAX Observatory, 2024).

In recent years, there has been a surge of proposals to introduce effective taxation schemes targeting the upper end of the wealth distribution, particularly focusing on ultra-high-net-worth individuals (Chancel *et al.*, 2022). These schemes aim to earmark the revenues generated from such taxes to help address the climate funding gap. For instance, a progressive wealth taxation scheme for the world's richest 0.1% individuals – imposing a 5% marginal net wealth tax rate on assets above USD 100 billion – even assuming 10% depreciation and 20% evasion, could raise about USD 1 100 billion per year globally. This amount is comparable to the total additional annual climate funding requirements of USD 1 800 billion by 2030 for low- and middle-income countries excluding China (WIL, 2023). A similar progressive wealth taxation proposal that imposes a 5% tax rate on billionaires, as suggested in OXFAM (2023), could generate approximately USD 1 700 billion annually.

In 2024, Brazil's G20 presidency spearheaded discussions on the need for international collaboration to introduce effective taxation of ultra-high-net-worth individuals. This initiative builds upon the G20's 2021 global agreement approving a common minimum corporate tax of 15% for large multi-national companies. The current proposal suggests a presumptive income tax based on wealth, mandating that individuals with over USD 1 billion in assets pay a minimum annual tax of 2% of their wealth (in contrast to the current effective tax rate of 0.3% for billionaires), which would generate approximately USD 200-240 billion in 2024[11] from

11 Extending the minimum 2% tax to centimillionaires (0.001% of all adult individuals globally) would generate additional revenues of USD 110-135 billion annually.

around 3 000 taxpayers. However, this baseline taxation proposal fails to address the regressive nature of taxation for centimillionaires. To create a more progressive tax system, a minimum annual tax of 3% would apply to individuals with wealth exceeding USD 100 million. This adjustment would ensure a progressive structure above the 99.99th percentile, potentially raising total revenues of about USD 550-690 billion per year in 2024[12] (Zucman, 2024).

IRENA's analysis of the socio-economic footprint of collaborative international finance follows the public-private partnership model described earlier, where financing is sourced from both public and private sources. Public contributions in IRENA's analyses are influenced by the Responsibility and Capability Index (RCI), thereby directly addressing the equity component of the socio-economic framework. The RCI has been assessed using the Climate Equity Reference Calculator (Holz *et al.*, 2019), a tool designed to evaluate the fair distribution of burdens in line with the UNFCCC principles (Dooley *et al.*, 2021; Holz *et al.*, 2018). Private contributions are governed by a wealth taxation scheme along the lines of current thinking as discussed above. The wealth taxation scheme applied in IRENA's analyses is derived from progressive scenario 2 in (WIL, 2022), significantly scaled down[13] to align with the targeted revenues throughout the analysis period (up to 2050).

5.2.3 How should collaborative international finance flows be distributed?

The distribution of finance flows among recipient countries is a crucial aspect of governance. Historically, various criteria have been used for this distribution, often lacking transparency and objectivity. Macro-economic indicators, such as per capita GDP, have frequently guided financial flows related to international collaboration.

More recently, in the context of climate finance, the Just Energy Transition Partnerships aim to accelerate the phaseout of fossil fuels (in South Africa, Viet Nam, Indonesia and Senegal). These partnerships focus on the justice pillar of the socio-economic framework. The literature has proposed various approaches to distribute international financing based on other pillars of the socio-economic layer. For instance, Fanning *et al.* (2023) focus on the equity pillar that allocates responsibilities for contributing to international finance funds and distributes these resources among recipient countries based on their cumulative carbon debts and credits after completing the transition.

During the transition process, it is essential to understand evolving needs within the broader context of governance development and domestic resource mobilisation. Key areas such as education, health and infrastructure significantly influence social value and help shape inequalities. Over the past five decades, tax revenue has remained below 15% of GDP in 86% of low-income countries and 43% of lower-middle-income countries (World Bank, 2024). In contrast, tax revenue in high-income countries has risen above 30% of GDP[14] (Bachas *et al.*, 2021). The rapid liberalisation of trade during the 1980s and 1990s contributed to the extremely low levels of domestic resource mobilisation for social value creation in the Global South

13 As the global wealth of ultra-high-net-worth individuals grows at a higher rate than the imposed minimum tax (with an observed pre-tax rate of return on wealth for these individuals averaging 7.5% [net of inflation] per year over the last four decades), revenues from this taxation scheme are expected to increase over time.

13 In the transition scenarios considered, the stock of wealth increases over time, necessitating the application of a 11% escalation factor to ensure that the average revenues align with the targeted 2022 revenues of the proposed taxation scheme in this reference.

14 The significantly higher GDP in high-income countries increases the absolute amount of tax revenues, as higher shares are applied to a larger economic base.

countries, drastically reducing custom duties and other taxes on international trade, which constituted a significant portion of total tax revenue in these countries (Piketty, 2020). International collaboration also plays an important role here, by supporting institutional reinforcement and promoting structural changes in international relationships. A country-by-country needs-based evaluation of spending and finance, which incorporates the evolution of domestic resource mobilisation to achieve the Sustainable Development Goals (SDGs), is outlined in a recent study (Kharas and McArthur, 2019), highlighting the relevance of the approach and its potential to improve high-level evaluations.

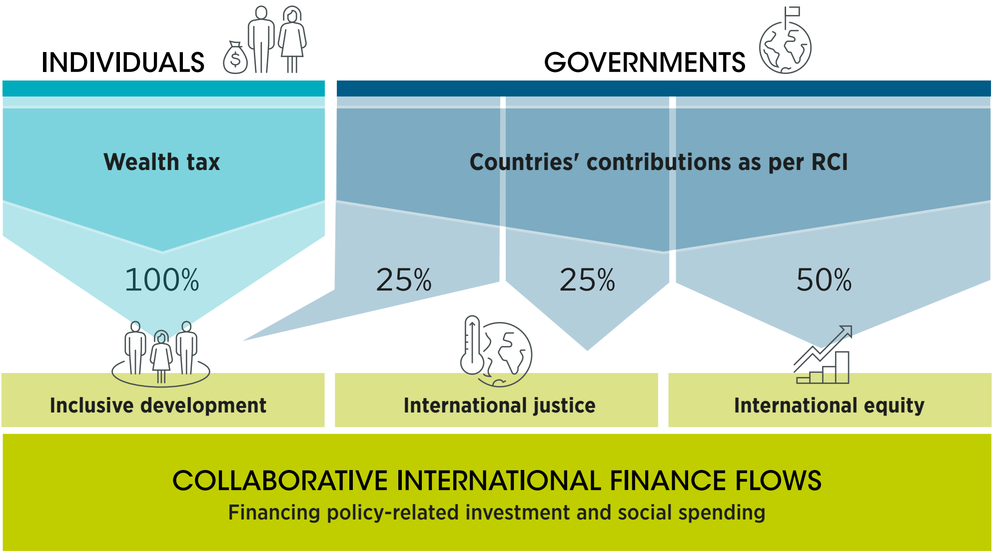
In the ongoing process to define the NCQG for climate finance under the UNFCCC to be agreed upon at COP29 in 2024, the relevance of a needs-based evaluation of climate finance is underscored. The UNFCCC Standing Committee on Finance is tasked with preparing a report every four years, on determining the needs of developing-country parties concerning the implementation of the Convention and the Paris Agreement. The first report was produced in 2020 (UNFCCC Standing Committee on Finance, 2021), and the second one is due in 2024. References to this needs-based approach are evident in parties' submissions to the NCQG process ('NCQG submission: India', 2024; 'NCQG submission: Zambia on behalf of AG', 2024; 'NCQG submission: Brazil on behalf of Group SUR', 2024).

IRENA's work on assessing the socio-economic footprint impacts of the energy transition adopts a needs-based approach linked to the three pillars of the socio-economic layer for distributing international finance flows. It does not aim to replace the country-specific bottom-up evaluation of actual needs, which must be addressed in international fora, processes and negotiations such as those occurring in the ongoing NCQG process within the UNFCCC.

Figure 5.4 illustrates how collaborative international finance flows might be structured. Allocations following a needs-based approach that is organised along the three pillars of equity, justice and inclusion. It goes without saying that the interplay of national priorities and complex multilateral decision-making processes may yield a different approach.

Half of the public contributions are allocated through the equity pillar, with the other half is evenly distributed between the justice and inclusion pillars. All private contributions (derived from wealth taxation of individuals) are channelled through the inclusion pillar. Under this pillar, all countries are beneficiaries, and fund allocation is proportional to the complementarity of the Human Development Index for each country. The distribution of funds via the justice pillar targets countries below a specified GDP per capita threshold and is based on the country's fossil fuel vulnerability as assessed through two dimensions: the capacity to finance a just transition (quantified by per capita GDP) and the economy's fossil fuel dependency (measured by the proportion of government revenue from oil and the share of employment in coal mining). Beneficiary countries of the equity pillar are those whose fair carbon dioxide (CO_2) emissions exceed the emissions predicted by the mitigation pathway, with funds allocated in proportion to the difference between fair and mitigation emissions.

FIGURE 5.4 Structure of collaborative international finance flows: Contributions and distribution in IRENA's socio-economic footprint modelling



Source: (IRENA, 2023b).
Note: RCI = Responsibility Capacity Index.

5.2.4 Using collaborative international finance flows

Once resources have been secured and distributed among countries, the final governance aspect of international financial collaboration flows is how these resources are utilised. This is a crucial factor in building trust and fostering effective collaboration.

An important body of literature has examined the investment required to achieve the SDGs (Bhattacharya *et al.*, 2022; Gaspar *et al.*, 2019; Kharas *et al.*, 2019; Turner *et al.*, 2021; UN ESCAP, 2020). Unfortunately, these studies often fail to comprehensively address the various dimensions of capital that should be considered (human, social, physical and natural), as well as the incorporation of adaptation and resiliency needs. Investment in natural capital (including ecosystem conservation and biodiversity), adaptation and resiliency measures, and social capital investment/expenditure are often not comprehensibly addressed.

In its socio-economic footprint analysis of collaborative international financing, IRENA has proposed a robust policy framework to guide the use of these financial flows for socio-economic modelling purposes. According to IRENA's welfare index results from previous socio-economic footprint modelling exercises (IRENA, 2019b, 2021; IRENA and AfDB, 2022), significant socio-economic gaps exist, particularly in the Global South, with the most notable deficiencies in the social and distributional welfare index dimensions, and to a lesser extent in the economic welfare index dimension. Additionally, re-distribution policies aim to bridge the gaps in both the distribution and economic welfare index dimensions. The directed social spending is intended to improve various public services crucial for social welfare (*e.g.* health, education, etc.), and bolster environmental protection efforts (*e.g.* climate adaptation and resilience; environmental and biodiversity conservation).

5.2.5 IRENA's international collaboration sensitivity analyses

Assessing the socio-economic footprint of the energy transition at varying levels of ambition regarding collaborative international finance flows offers valuable insights that inform policy making and its relevance for the transition. In recent years, IRENA has conducted several sensitivity analyses of its energy transition roadmap (1.5°C Scenario), exploring different levels of financing, where the sourcing, distribution and utilisation of these funds have been guided by aforementioned policies.

Analyses have been conducted on average international finance flows for the period 2023-2050, ranging from USD 0.3-2.0 trillion per year. According to IRENA (2021), a publicly sourced international collaboration of USD 0.3 trillion per year was initially introduced as part of the transition scenario's policy basket, which addresses the policy investments and expenditures required for the energy transition. In IRENA (2022f) and IRENA and AfDB (2022), a sensitivity analysis of collaborative international finance was developed, examining two levels of average publicly sourced finance: USD 0.3 trillion and USD 1.0 trillion per year from 2023 to 2050. This analysis also focused on addressing gaps in the socio-economic layer. A recent WETO edition (IRENA, 2021) included a sensitivity analysis that complemented publicly sourced international financing with privately sourced finance. One transition scenario, based solely on publicly sourced finance of USD 1.0 trillion per year (averages over 2023-2050) was compared to another scenario where public finance was supplemented with an equal amount of privately sourced finance through wealth taxation. This approach results in USD 2.0 trillion per year, averaged over the same period (Figure 5.5) (IRENA, 2021).

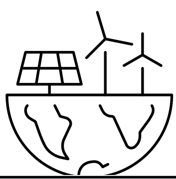
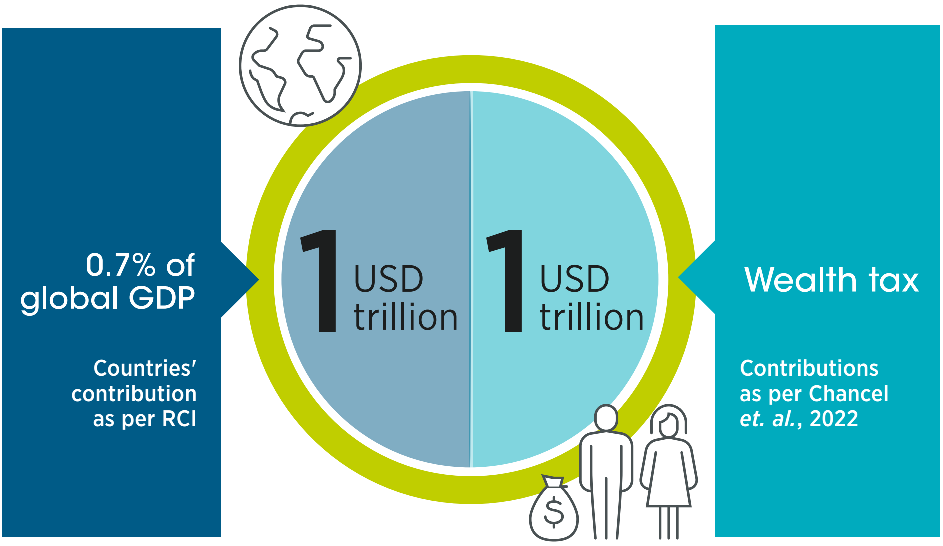


FIGURE 5.5 **Contributions to the Global Energy Transition Fund from public sector and wealth taxation**



Source: (IRENA, 2023b).
Note: GDP = gross domestic product; RCI = Responsibility Capacity Index.

This section provides a consolidated comparison of all sensitivity analyses of collaborative international finance (USD 0.3, 1.0, and 2.0 trillion per year in average over 2023-2050) focusing on the socio-economic impact.

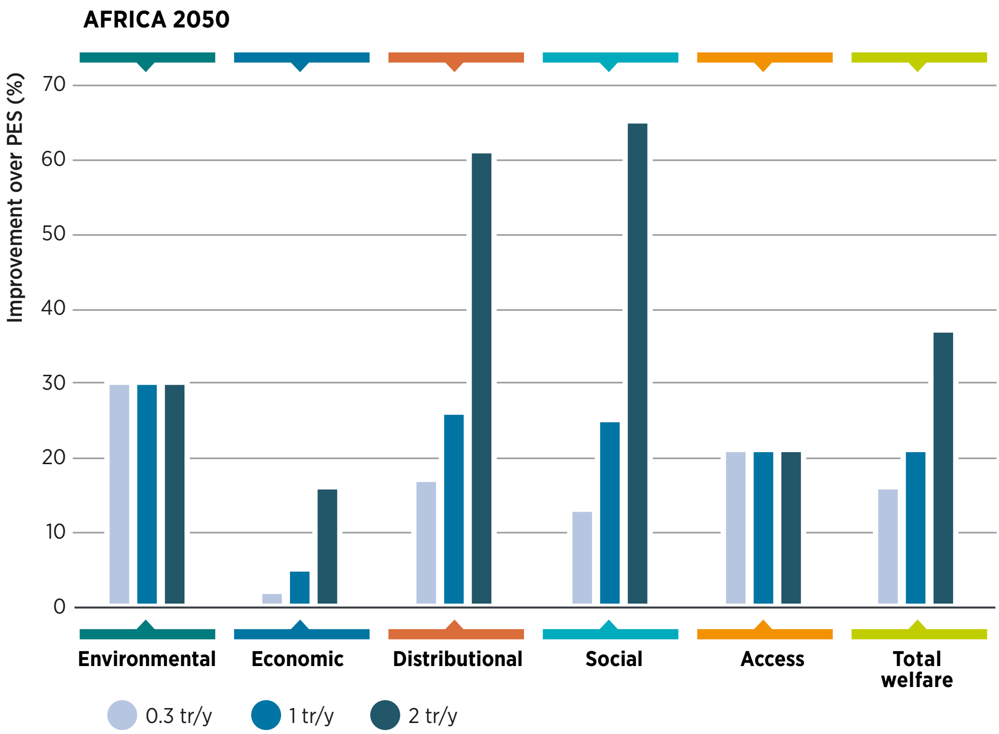
As previously discussed, the primary indicator used by IRENA to assess the socio-economic footprint of the transition, and particularly the evolution of gaps in the socio-economic layer, is IRENA's welfare index with its five dimensions (environmental, economic, distributional, social and access). The environmental and access dimensions are addressed by the energy transition roadmap itself through the evolving energy mix and energy balances.

The role of international financing and the accompanying policies to guide its sourcing, distribution and use, is focused on addressing the socio-economic gaps in the economic, distributional and social dimensions of the welfare index. Previous analyses (IRENA, 2021, 2022f; IRENA and AfDB, 2022) have documented that these dimensions highlight the most significant deficiencies in the socio-economic footprint of the energy transition, particularly in the Global South countries.[15]

17 Note that in the Global North countries, the disparity in the economic welfare dimension is small, while gaps in the social and distributional welfare dimensions remain relatively pronounced. Furthermore, the Global North countries frequently exhibit substantial gaps in the environmental welfare dimension, driven by high consumption of materials linked to their significant aggregate economic activity.

Collaborative international finance, together with additional policies that direct financial resources towards social value creation, as well as redistributive policies, hold substantial potential for enhancing welfare outcomes as assessed against the PES. Figure 5.6 presents the socio-economic footprint impact of collaborative international finance in Africa, highlighting the difference in the welfare index between the PES (which excludes collaborative international finance) and the transition scenario (1.5°C Scenario) under varying levels of financing. As illustrated in Figure 5.6, the most significant benefits of international collaboration finance accrue in the targeted economic, distributional and social dimensions of the welfare index. The scale of this finance critically influences the improvements observed over the PES. For an annual international collaboration finance level of USD 2.0 trillion per year (averaged over 2023-2050), improvements in the social and distributional indices exceed 60%, while the economic dimension approaches a 20% improvement. These improvements over the PES in key welfare dimensions, where socio-economic gaps have persisted for decades and are expected to continue unabated under mainstream transition narratives, represent a robust basis for crafting compelling transition narratives that can mobilise the global collaborative effort essential for tackling climate change and other global challenges.

FIGURE 5.6 Difference in welfare between the Planned Energy Scenario and the 1.5°C Scenario with different levels of collaborative international finance flows, by dimensional contributions, by 2050:

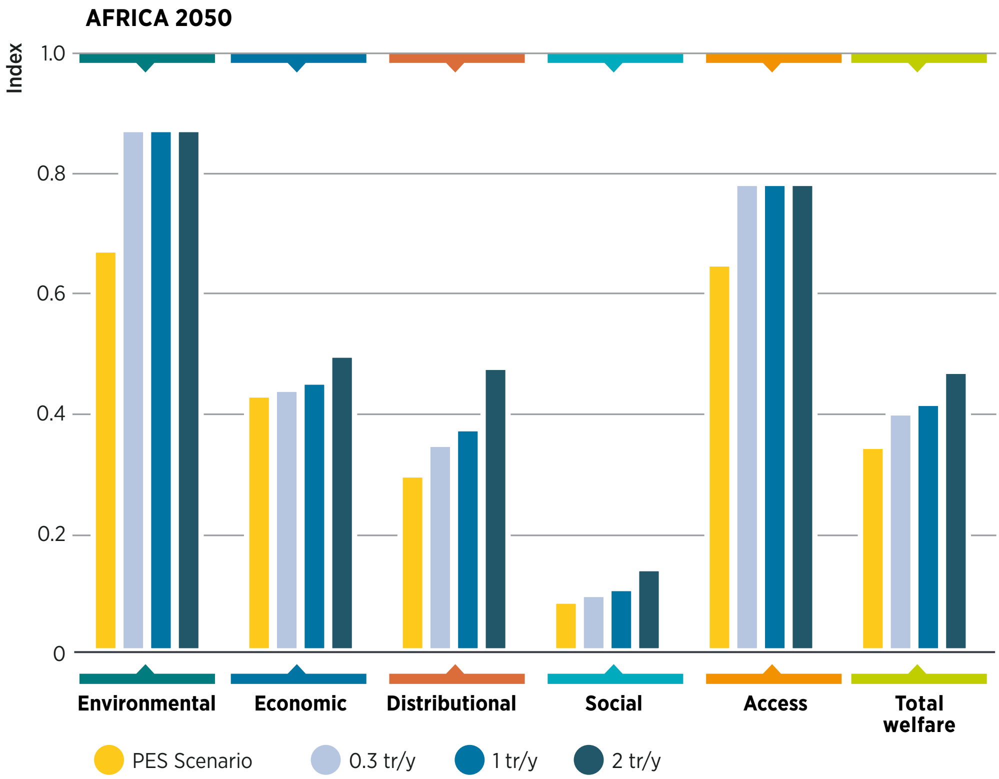


Source: (IRENA, 2023b).

Note: PES = Planned Energy Scenario; tr/y = trillion per year.

Beyond the improvements over the PES, examining the absolute welfare index is vital for gaining deeper insights. Figure 5.7 presents the absolute values of the welfare index and its five dimensions for Africa by 2050 in the PES and the 1.5°C Scenario at various levels of collaborative international finance. The welfare index and its dimensions are structured on a scale ranging from 0 (low performance) to 1 (high performance). Despite improvements in the economic, distributional and social welfare dimensions brought about by increasing levels of international collaboration finance, significant gaps remain, even with the highest level of international collaboration finance considered in this analysis (USD 2.0 trillion per year). Persistent gaps[16] stand at approximately 50% in the economic and distributional dimensions, and exceed 85% in the social dimension.

FIGURE 5.7 **Overall welfare index and dimensional welfare indices for the Planned Energy Scenario and the 1.5°C Scenario with different levels of collaborative international finance flows, by 2050: Africa**



Source: (IRENA, 2023b).

Note: PES = Planned Energy Scenario; tr/y = trillion per year.

16 An index value of 1 indicates that the gap has fully closed.

The large socio-economic gaps projected for 2050 in Africa (Figure 5.7) indicate a profound inadequacy in the socio-economic layer, despite substantial international financial collaboration efforts. Addressing this will require more than just financing. It will require a focus on improving the socio-economic structural components that have historically generated and perpetuated these gaps and transitioning towards improved structures that prevent the perpetuation of these gaps. Crafting an engaging transition narrative aimed at fostering widespread collaboration to address climate change will thus demand both international co-operation and structural reform. The next section will delve into the structural facets of the energy transition.

5.3 The need to consider structural changes in the economy

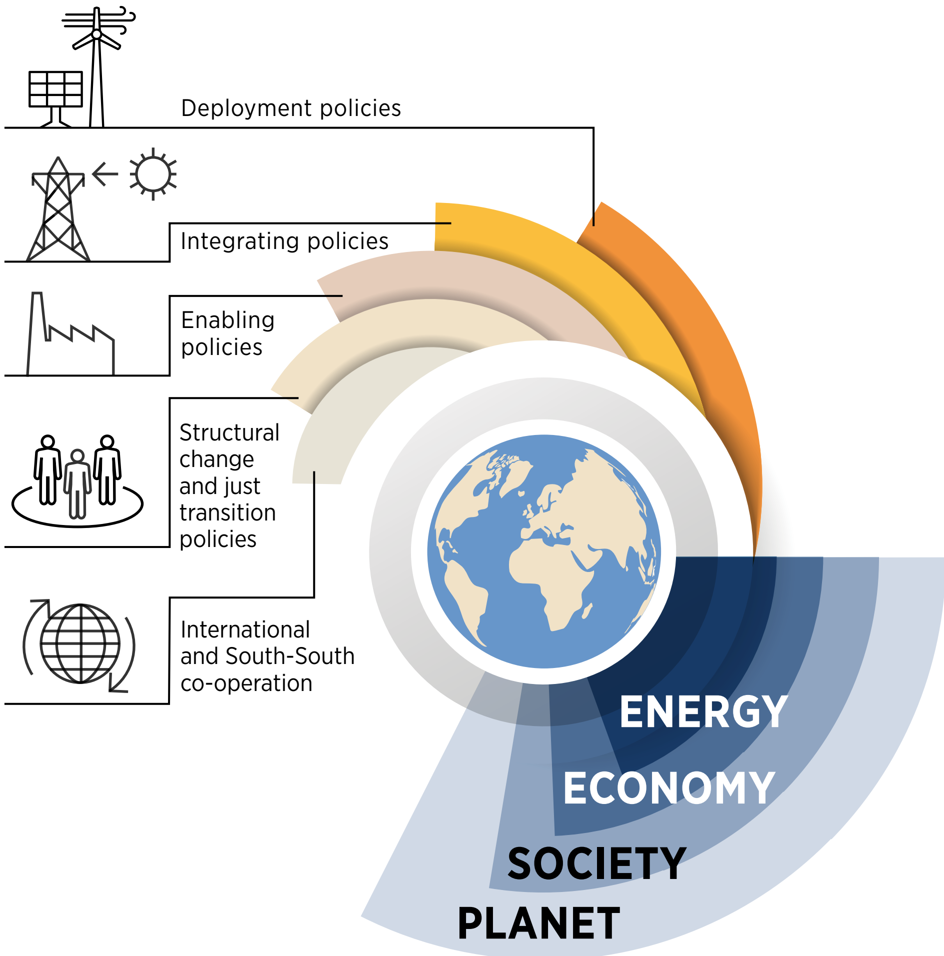
As discussed in Chapter 1, limiting global warming to 1.5°C necessitates very high rates of mitigation and a significant intensification of the technological transition, including the deployment of renewables and improvements in energy efficiency. Structural changes in the economy could reduce the scale of this challenge. A larger economy requires greater volumes of energy and material resources, but their extraction and use could jeopardise planetary boundaries in addition to climate concerns. However, if structural changes could decrease the overall demand of the global economy on the natural world, it may be possible to achieve higher transition rates with the same level of technological change. Under the current business-as-usual assumptions, the global economic system is projected to grow at around 3% annually, doubling in size by 2050. To accelerate the achievement of net-zero emissions, it will be essential to limit economic growth (in terms of physical demand) while ensuring welfare and shared prosperity.

The key challenge is to understand how to reduce global economic activity while enhancing shared prosperity worldwide and winnowing persistent socio-economic disparities. Policies aligned to this objective would aim at a redistribution and rebalancing of global economic activity among countries and regions, prioritising growth where it is most needed with the aim of meeting all human and environmental needs.

Given the criticality of the current multi-crisis (including climate change, biodiversity loss and inequality), the potential for structural changes warrants thorough exploration. IRENA aims at providing value by advising policy makers and society on the necessary policies for navigating various transition pathways in this space of possibilities, while addressing gaps in the socio-economic layer and quantifying the resulting socio-economic impacts.

A holistic approach with a clear focus on the desired outcomes is essential to addressing the systemic complexity within which change must occur. This complexity involves an embedded configuration of different systems (energy, economy, society, planet) characterised by multiple and strong feedback loops, all interfacing with a multi-layered policy ecosystem (Figure 5.8). The volume and intensity of feedback across systemic and policy layers are likely to be amplified during rapid transitions and periods of systemic destabilisation resulting from the ongoing multi-crises, including climate change, biodiversity loss, economic disparity and social unrest). Ignoring this feedback is not a viable option for achieving a feasible and sustainable transition. The feasibility of the transition hinges on the implementation of social and environmental policies in an integrated manner, underpinning a deep eco-social transformation that simultaneously addresses gaps in the socio-economic layer and the climate and biodiversity crises.

FIGURE 5.8 **Embedded systems under the influence of a multi-layered policy ecosystem**



Structural change invariably faces inertia and resistance from certain entrenched interests. Uncertainty and insufficient understanding of the new structures are the main barriers to progress. Effectively understanding and harnessing the political economy of structural changes is vital for planning and implementing a successful and feasible transition.

In recent years, there has been a surge in literature examining various facets of the political economy of structural socio-economic changes. From the profound inter-connection between climate and social goals (Lankes *et al.*, 2022) to evidence confirming that integrated policy action across systemic layers enhances public support for climate initiatives (Bergquist *et al.*, 2020), all findings underscore the necessity of a holistic approach to the transition that addresses its political economy.

A review of the literature on the political economy of the energy transition reveals a predominant focus on the factors driving technological change,[17] primarily within the energy sector. This narrow scope highlights significant gaps in understanding the factors that drive institutional change and the need for a more holistic perspective on the economic system (Agbaam *et al.*, 2023). Brand *et al.* (2021) propose shifting from a focus on planetary boundaries to societal boundaries,[18] shedding light on the underlying structural conditions of unsustainability and the social conflicts embedded within them. Societal boundaries are thresholds collectively defined by societies, which they agree not to trespass. These boundaries encompass economic, social and political aspects, including poverty, inequality, ecological degradation, injustices, subordination, exploitation, consumption and the defence of common goods. Such collectively defined self-limitations are essential for shared prosperity and are rooted in the principle of social freedom – specifically, the freedom from living at the expense of others. These must be defined through social dialogue and political negotiations, following robust democratic processes to ensure societal legitimacy (Brand, Ulrich *et al.*, 2021).

Governance emerges as a critical issue within the political economy of climate change. An exploration of the interaction between social systems and planetary boundaries (see section 4.3.1), particularly the dynamics among experts, citizens and policy by Pickering and Persson (2020) delves into the importance of providing democratic legitimacy through an iterative dialogue among stakeholders to enhance earth system governance. Ensuring a solid social foundation for addressing governance challenges is key, and Ensor *et al.* (2021) propose a human-rights-based approach to governance as a pathway for navigating the political economy of structural change (Ensor, Jonathan and Hoddy, 2021). Furthermore, the political economy of the proposed transition towards participatory socialism, as outlined in Piketty (2020), completely hinges on deepened and enhanced democratic deliberation.

17 Factors such as vested interests, advocacy coalitions, green constituencies, path dependency, external shocks, the policy and institutional environment, political institutions and fossil fuel resource endowment play significant roles in this context.

18 "Collectively defined thresholds that societies establish as self-limitations and conditions for a good life for all".

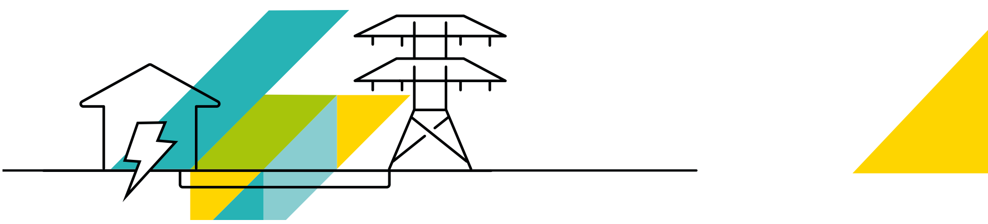
The political economy of structural change is inherently complex. In the context of transitioning to a "climate-just finance system", Dafermos (2023) identifies important challenges and potential barriers such as reluctance in the Global North to acknowledge contracted climate debt and its implications, and the need for capacity building in the Global South to effectively direct funding towards social value creation by addressing socio-economic disparities.

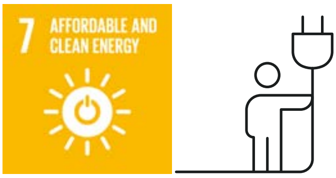
IRENA's socio-economic footprint analysis can significantly contribute by addressing the information deficit related to transition processes that integrate both technological and socio-economic aspects. With this goal, IRENA's future energy transition analysis will widen its scope beyond the pure technological transformation within a business-as-usual economic and social framework. It will explore socio-economic structural changes that could be relevant for the feasibility and effectiveness of the transition, by contributing to an engaging narrative while boosting the capacity to tackle current multi-crises. Achieving this requires implementing structural changes in transition scenarios, supported by comprehensive policy frameworks that direct the structural change towards social value creation and undertake socio-economic modelling to assess the associated socio-economic footprint. By offering policy makers and society with a broader array of technological and socio-economic transition pathways, along with their respective implementation requirements and socio-economic footprints, this approach would inform transition planning and policy making, as well as strengthen the political economy of the transition.

5.4 Deep dive into energy access

5.4.1 Energy access as a critical component of energy transition

SDG 7 aims to "ensure access to affordable, reliable, sustainable, and modern energy for all". SDG target 7.1, which focuses on achieving universal modern energy access by 2030, is a fundamental cornerstone for designing a just and inclusive energy transition aligned with the 1.5°C climate goal. The energy transition would lack significance if it fails to deliver access to basic energy services for every household, farm, enterprise, school and clinic: the basic tenets for countries' industrialisation and socio-economic development objectives. Without energy access, the economic, social and environmental goals that the energy transition seeks to achieve cannot be realised.





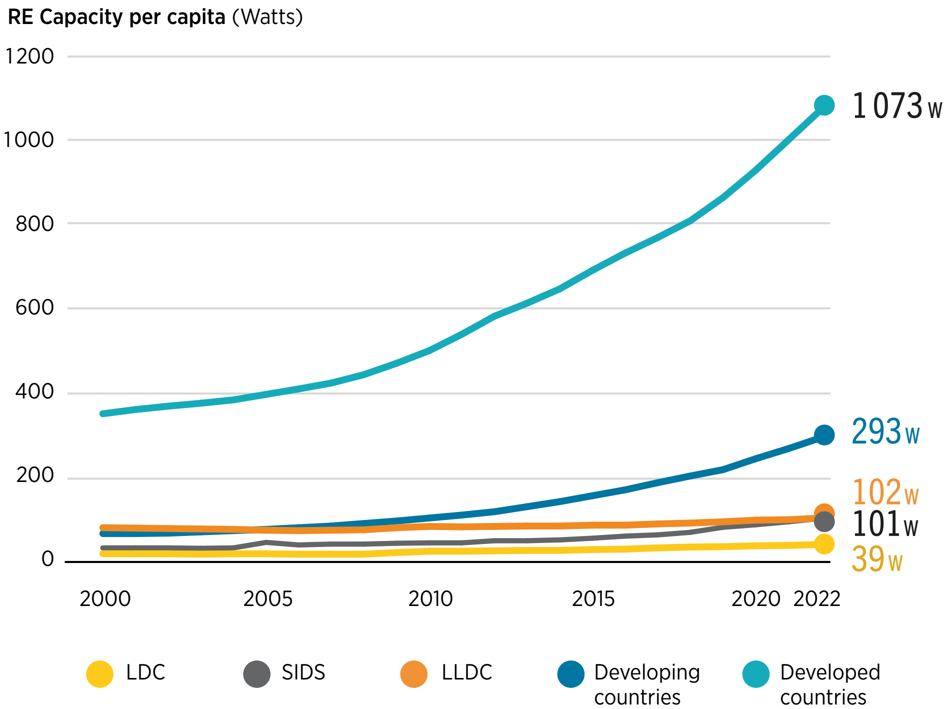
According to the latest projections (IEA *et al.*, 2024), the SDG 7 targets will not be met. An estimated 660 million people in developing countries will remain without access to electricity, and 1.8 billion people without access to clean cooking by 2030, given the current pace of progress. Unlike other SDG 7 targets, which show consistent yearly improvement, the goal of universal energy access has experienced a reversal in progress as population growth has outstripped advancements in access, particularly in Sub-Saharan Africa where there is an increasing access deficit.

The failure to achieve energy access targets has dire consequences both for development and the energy transition agenda. Lack of access to clean cooking is linked to 2.5 million premature deaths, mostly of women and children, and contributes to 1.5 billion tonnes of CO_2 equivalent (tCO_2eq) emissions. Due to the weak and often non-existent electricity grids in many developing countries, backup fossil-fuel-based generators are widely used, providing 9% of electricity consumption in Sub-Saharan Africa and 2% in South Asia. In Sub-Saharan Africa, it is estimated that generators account for the majority of power sector emissions of nitrogen oxides (NOx) and fine particulate matter (PM2.5), with their contribution to PM2.5 emissions equivalent to 35% of the emissions from the entire transportation sector (IFC, 2019). Energy access is an enabler of health services and improved health outcomes, education, communication, food safety, security and other development indicators, highlighting the extensive impact of the current lack of progress, impeding the achievement of several other SDGs.

The energy access divide persists alongside concerns about other disparities, such as the global decarbonisation divide as some countries still lack the necessary policy tools, investments and skills required for industrial decarbonisation (IRENA, 2021). The geographic concentration of renewable energy deployments in only a few countries and regions, along with inequalities in social protection and wealth, further complicates the situation. Energy access presents a particularly mixed picture: while 91% of the global population has access to electricity, only 16.7% of Sub-Saharan Africans do. This mirrors the divide in renewable energy deployment, with G20 countries projected to account for more than 80% of global renewable capacity by 2030. An energy transition that excludes nearly half the global population will not meet climate or social justice targets. On the other hand, linking the energy access and decarbonisation agendas could offer legitimacy to the global energy transition, securing beneficial outcomes for all regions and peoples.

To secure an energy transition that is aligned with the 1.5°C pathway, a virtuous circle of technology, policy, finance and innovation is needed. The costs of renewable electricity continue to decline globally, making renewables the most affordable power generation option in most regions. However, the exploitation of renewable energy remains low in countries facing access deficits, despite their resource abundance. Developing countries have the lowest renewable energy generating capacity: 293 watts per capita relative to 1 073 watts per person in developed countries (Figure 5.9). Providing access to technology and skills, capacity building and affordable finance could significantly unlock the full potential of developing countries to contribute to the global energy transition, in turn providing them with the infrastructure and revenues necessary to meet their own energy access goals.

FIGURE 5.9 Renewable energy generating capacity per capita by country, 2000-2022



Notes: LDC = least-developed country; LLDC = landlocked developing country; SIDS = small island developing state.

5.4.2 Energy access as a socio-economic dimension of energy transition

Access to affordable, reliable, sustainable and modern energy has been globally recognised as essential for development since the establishment of a dedicated and standalone goal (SDG 7) in 2015. Its roots can be traced back to the World Summit for Social Development held in Copenhagen in 1995, which placed the needs of the people squarely at the centre of development. The SDGs' vision of leaving no one behind is one of the six Guiding Principles of the United Nations Sustainable Development Cooperation Framework. Within this framework, energy access is recognised as one of six key transitions catalytic for accelerating progress towards the SDGs.

As noted earlier, energy access is a development challenge primarily concentrated in the Global South. A narrative that focuses on maximising the benefits of the ongoing transition while minimising its adjustment burdens does not adequately represent the needs of populations that have yet to get onto the transition ladder. For these populations, a different narrative is necessary – one that recognises that their baseline entails no energy to begin with and uses this context to create a transition pathway that reflects this reality. Only in doing so can the transition agenda with its basic tenets of fairness, equity and justice become relevant and embraced by all, leaving no one behind.

This does not imply that energy access and the socio-economic considerations that underly it should be seen as separate from the energy transition. On the contrary, placing socio-economics at the centre of the energy transition – through narratives, analyses and financial mechanisms – could accelerate progress through carefully selecting policies, technologies, financial instruments and skills development, among other strategies. There is already a common ground between the underlying objectives of energy access and other SDGs, such as eradicating poverty, generating employment, reducing inequality and fostering inclusive societies, as discussed in chapter 4. The spatial difference in energy transition for populations with and without energy access should be viewed as an opportunity for learning, offering an illustrative pathway on what should be followed, and more importantly avoided, for populations gaining first-time energy access. The deadline for achieving the SDG 7 targets is fast approaching (IEA *et al.*, 2024), leaving little time to develop new narratives and advocate for a new agenda. Therefore, it is essential for the socio-economics of the energy transition – encompassing definitions, analyses and narratives – to address the unique needs of those populations that are yet to gain access to modern energy.

5.4.3 Accounting for local context

Progress on energy access varies significantly across and within regions, highlighting the need to account for contextual barriers. Economic factors in access-deficit countries include an uncertain macro-economic outlook, high levels of inflation, debt distress and inequitable distribution of finance and other resources (IEA *et al.*, 2024). Overcoming these structural barriers requires a tailored approach. For instance, deploying debt instruments in nations experiencing debt distress and high inflation would not only contradict public welfare interests, but also render solutions unaffordable. Concurrent with suitable financing and policy measures, it is important to restructure financial systems to enable heavily indebted countries – who have historically contributed the least to climate impacts – to participate equitably in the energy transition. This principle underpins the concept of a just and fair transition (see section 4.1).

The local context should also be considered when selecting technologies for deployment. In Sub-Saharan Africa, which has the highest electricity access deficit, electricity supply is largely monopolised by government-owned utilities that control generation, transmission and distribution, limiting private sector participation. These structures must evolve to accommodate the energy transition, allow for fair pricing and competition, and prevent stranded assets. A policy shift could unlock the full potential of the distributed renewable energy (DRE) sector, which has proven to be both cost competitive, and the most feasible means of supplying electricity to remote and low-income communities that constitute the majority of those without access to electricity.

Some trends may offer a positive outlook depending on how they are harnessed. While serving the remaining unelectrified population is more challenging due to its remoteness, there is a parallel trend of rapid urbanisation in countries facing access deficits, which averaged 45% in 2023 (Statistica, 2023). Projections indicate that more people will be living in urban areas than rural ones, potentially overcoming the primary challenge of costly grid extension to rural communities and leading to accessible and affordable services. As regards clean cooking, a young and educated urban population may be more receptive to adopting modern technologies (Energy Sector Management Assistance Program, 2021), including electric cooking. Recent statistics (Stoner *et al.*, 2021) already show a more rapid increase in electric cooking than in liquefied petroleum gas use in urban areas. However, these trends also pose new challenges for other dimensions of energy access such as reliability of power supply, capacity and legality of connections, which are being observed in urban informal settlements. If mitigation measures for these challenges are not adequately planned, it could increase the use of polluting diesel generators and kerosene, exacerbating air pollution and negatively impacting health and climate.

The above arguments underscore the need for an energy transition that is owned by countries and tailored to specific national and local contexts. It must consider each country's readiness, capacities and needs, as well as the political economy, including the role of utilities in the transition and the different fuels and technologies for clean cooking. It is becoming increasingly evident that the shift to clean cooking will not entail a complete switch in fuels, but rather a combination of technologies and fuels that serve different purposes. Alongside the clean primary technology, a bundle of "clean stacking" options would help further the health and climate gains that underpin the SDG 7 agenda.

5.4.4 Implementation progress and gaps

The world is not on course to achieve the SDG 7 targets for energy access. In 2022, an estimated 79% of the population in Sub-Saharan Africa and 33% of people living in Central Asia and Southern Asia were still using polluting fuels and technologies for cooking (IEA *et al.*, 2024). The year 2022 marked a reversal in progress on efforts to expand access to electricity, with the number of people living without it increasing for the first time in over a decade.

Sub-Saharan Africa is home to most of the global population without access, and the disparity between regions is widening. Sub-Saharan Africa now accounts for 83% of the global access deficit, up from 50% in 2010. Eighteen of the 20 countries with the largest access deficits in 2022 are in Sub-Saharan Africa.

This trend of incremental changes at best or reversal of progress should not continue, given the scale of the immediate impacts of inadequate energy access. Residential solid fuel burning accounts for up to 58% of global black carbon emissions and emits 1 $GtCO_2$/year – approximately 2% of global emissions (World Bank, 2019). In 2020, total emissions from the cooking sector were estimated at 1.69 $GtCO_2eq$, with 1.30 Gt (77%) stemming from non-renewable biomass. Addressing these emissions would significantly contribute towards the 37 Gt reduction needed from 2022 levels to achieve net-zero emissions in the energy sector by 2050, while also realising significant development impacts (UN Energy, 2023). Reducing the cooking sector's CO_2 emissions to net zero by 2050 is viewed as one of the most immediate and cost-effective solutions. Furthermore, emissions due to lack of electricity access are also substantial. These may be viewed as part of the cooking-related emissions, since electricity is an important source of clean cooking energy that un-electrified populations currently lack. Also, emissions arise from the widespread use of diesel generators and kerosene, which serve as either primary or secondary sources of electricity for heating, lighting and various productive applications in sectors such as health care, education and agriculture.

The energy access gap is widening at a time when the solutions to the problem are well known. Renewable energy technologies have proven effective in delivering energy access. The essential requirements for an energy transition include building the necessary infrastructure, making substantial investments in both grid and off-grid solutions, advancing an evolved policy and regulatory framework that facilitates targeted investments, and strategically realigning institutional capacities to ensure that skills and capabilities match the demands of the new energy system. These same factors are deemed necessary to achieve universal access to modern energy (IEA *et al.*, 2024), suggesting that a holistic approach should be adopted for SDG 7. Numerous technological solutions are available, cost competitive with fossil fuels and ready for deployment. The foundational elements – stable energy systems, reliable regulatory and financial policy frameworks, ambitious policy goals and appropriate markets, including regional ones – are increasingly available or can be realised. It is time to translate these components into action.

5.4.5 Closing the gaps

According to the SDG 7 tracking report (IEA *et al*., 2024), universal access to electricity as well as clean cooking requires investment, policy support and the deployment of renewable energy. We will explore the opportunities under each of these areas, focusing on different technological solutions.

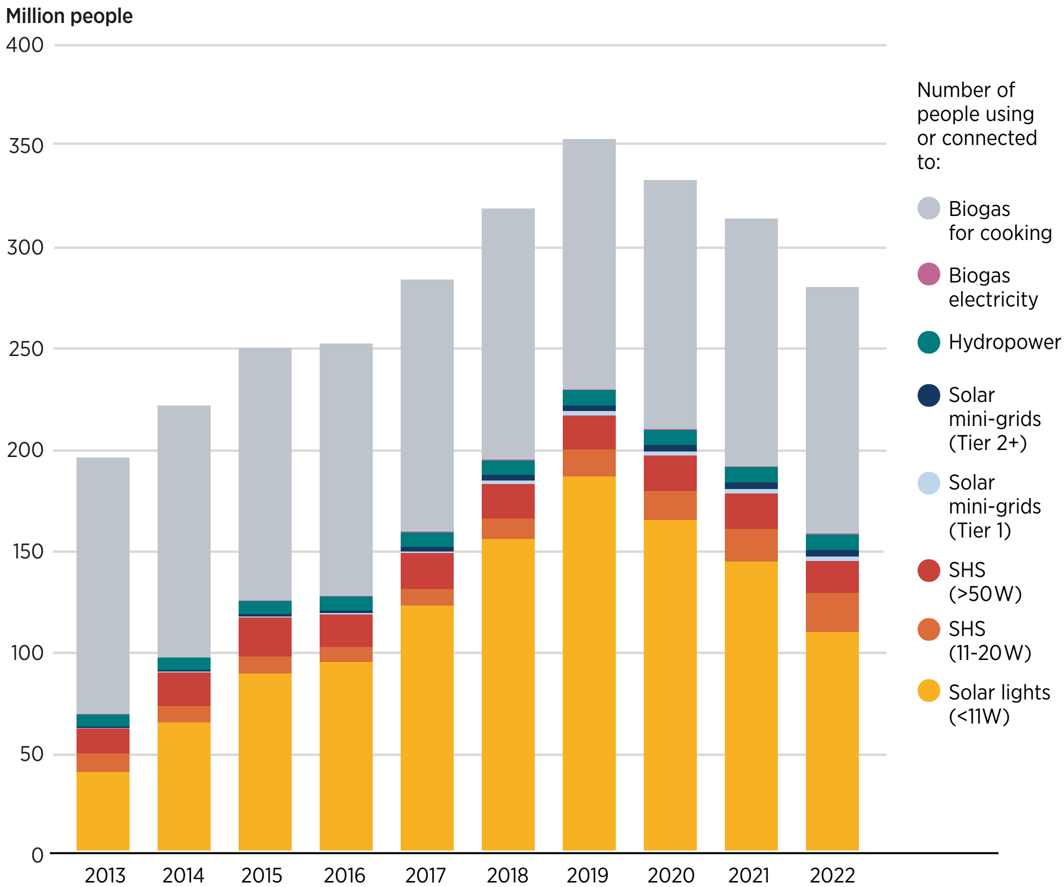
Distributed renewable energy (DRE)

DRE is a proven technology for achieving access to electrification, given that most of the population without access live in remote communities where extending the grid is not cost-effective. As of 2022, about 280 million people have gained access to energy using off-grid technologies (Figure 5.10). The least-cost electrification model estimates that an additional 670 million people will gain access via off-grid renewables. DREs can be deployed rapidly, providing immediate benefits.

However, several challenges need to be overcome, especially those that impede the large-scale deployment of DRE. Most DRE initiatives have been led by the private sectorbut investors face risks they are often unwilling to take. Target communities are typically remote and dispersed, have low and seasonal income affecting their ability to pay for services, and have limited economic activity that impacts revenue generation. The high upfront cost of finance that the private sector must bear, bureaucratic red tape, and uncertain policy and regulatory environments – such as what will happen to the assets when the grid eventually arrives – pose further challenges. This suggests that DRE cannot expand without strong financial and regulatory support from the public sector. Failing to tackle these challenges will continue to stifle the development of the DRE sector.

Productive use offers a significant opportunity to realise the full potential of both grid and off-grid electrification and enhance their sustainability. In rural communities, productive uses such as solar water pumps, cooking and cooling solutions, agro-processing and a wide range of equipment for micro-enterprises contribute to socio-economic development and improve the quality of life. Collectively, these initiatives can increase incomes and boost productivity to levels necessary to make rural electrification viable.

FIGURE 5.10 **Population with access to off-grid renewable energy technologies, 2013-2022**



Source: (IRENA, 2023d).

Note: W = watt; SHS = solar home system.

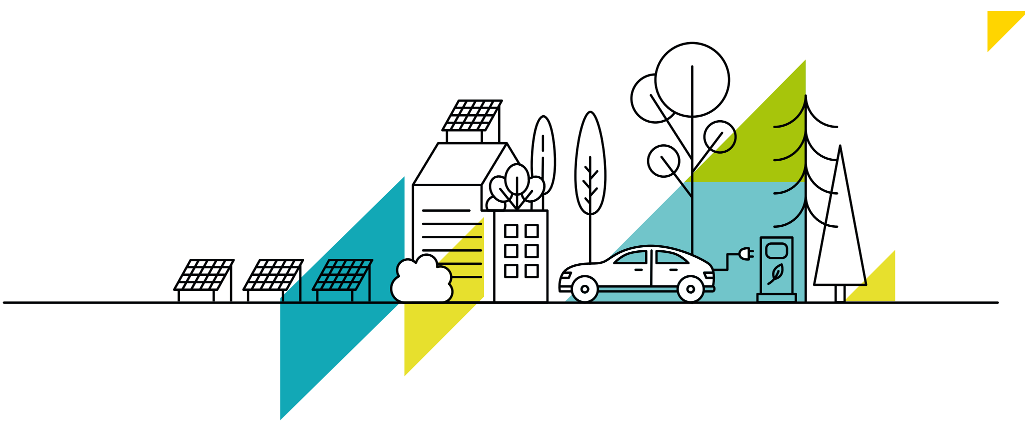
Renewables-powered grids

Relying solely on either grid or off-grid solutions is insufficient to ensure comprehensive energy access in all its dimensions. Achieving SDG target 7.1 by 2030 requires a combined approach that includes grid, mini-grid and standalone off-grid solutions. Sub-Saharan Africa, which experiences the largest access deficit, has significant untapped renewable energy potential. In 2018, only 20% of the electricity generated in Africa came from renewable sources. Although two-thirds of all newly added global energy capacity was based on renewable sources, just a mere 2% of this new generating capacity was in Africa (IRENA *et al.*, 2022a).

To harness this renewable energy potential, investments, effective planning for renewable energy integration in new power systems, regional co-operation – given the varied renewable energy resources among countries – and technology and knowledge transfer are essential. Finance and technology needs were clearly identified at the formulation of the SDGs, particularly with indicator 7.a.1, which focuses on "International public financial flows to developing countries in support of clean energy research and development and renewable energy production, including in hybrid systems".

The latest SDG 7 tracking report (IEA *et al.*, 2024), however, indicates that this indicator is off track. Renewable energy investment remains concentrated in a limited number of countries and is focused on only a few technologies. Also, 85% of global renewable energy investment benefited less than 50% of the world's population, and Africa accounted for only 1% of additional capacity in 2022. Investments in off-grid renewable energy solutions in 2021 amounted to USD 0.5 billion (IRENA *et al.*, 2023) – far below the USD 15 billion needed annually to achieve the 2030 target. While many technology options exist, most investments were directed towards solar photovoltaic and wind power, with 95% allocated to these technologies (IRENA *et al.*, 2023). It is crucial that greater funding flows into other energy transition technologies such as biofuels, hydropower and geothermal energy, as well as sectors beyond power that currently have lower shares of renewables in total final energy consumption, such as heating and transport.

The progress report also indicates that financial flows continue to be dominated by debt, accounting for two-thirds of the flows in 2022. Given the ongoing concerns of currency devaluation and over-indebtedness in many countries with energy access deficits, and their minimal contribution to climate change, a larger share of non-debt instruments should be utilised. This approach would help protect the economies of these countries, thus maintaining their ability to pay for energy services.



Clean cooking

Despite the slow progress in achieving the goal of access to clean cooking, several important positive developments in recent years could shape the future trajectory if sustained. An increasing number of countries have recognised clean cooking as an important development agenda and have established targets and policies to address the challenge. Among the 185 countries whose NDCs were reviewed in (IRENA, 2023e), 52 included various forms of cooking solutions and long-term strategies in their NDCs including improved cookstoves, liquefied petroleum gas, biogas and sustainable biomass. An increasing number of countries are developing clean cooking strategies and roadmaps, as well as integrated energy plans that include both electrification and clean cooking.

Similarly, some progress has been observed in the financing of clean cooking initiatives. In the recent Clean Cooking Summit in Africa, a financial commitment of USD 2.2 billion was announced, marking the largest commitment to date. This commitment followed other global events that highlighted clean cooking: at COP 28 the Global eCooking Coalition (GeCCo) was launched with a pledge of at least EUR 10 million for electric cooking; at the Africa Climate Summit, USD 26 billion was pledged towards renewable energy and adaptation, including clean cooking; and at the 2019 UN Climate Action Summit, the World Bank launched its USD 500 million Clean Cooking Fund. It is crucial to ensure accountability for these funds, particularly the distribution of these funds between actual projects on the ground and administrative or analytical expenses; between renewables- and non-renewables-based solutions; as well as across regions, countries and socio-economic groups. This can be achieved by tracking financial flows towards clean cooking, akin to the renewable energy finance tracking conducted by IRENA.

The increasing involvement of the private sector, utilisation of climate and public finance to mitigate the risks of private sector investments, and the introduction of innovative business models targeting last-mile connectivity have narrowed the access gap by 16% compared to 2010 levels. However, the current pace of progress is not enough to keep up with population growth. There is pressing need to intensify and scale up these proven measures in the run-up to 2030, particularly in the 20 countries with the largest access deficits, which account for 74%of the global population without access to clean cooking. Notably, half of these countries are in Sub-Saharan Africa.

The enabling roles of policy and finance become evident when examining progress across various technologies, including both grid and off-grid electrification and clean cooking initiatives. The SDG 7 tracking report indicates that an annual investment of USD 30 billion is needed from 2021 to 2030 to achieve electricity access, along with an additional USD 6 billion for clean cooking. In 2022, developing countries attracted USD 75 billion worth of investments within the broader renewable energy sector. However, the DRE sector within these countries attracted less than USD 4 billion over the past ten years. These figures highlight the DRE sector as a microcosm of the overall financing landscape, while demonstrating its immense impact. Over the past decade, more than 200 million people have gained access to electricity through decentralised renewables, with just USD 4 billion spent. From the return-on-investment perspective, this is highly significant (IRENA *et al.*, 2023). It also illustrates that while continued innovation in technology and additional measures remain important in closing the energy access gap, prioritising investments and financing for proven solutions, coupled with creating an enabling policy environment, can provide immediate solutions for accelerated progress. In addition, clean cooking presents a high rate of return on investment; the required annual investment of USD 4 billion to achieve universal access by 2030 is modest compared to the USD 2.4 trillion a year (ESMAP, 2020) it costs the world annually to cook using polluting fuels. This further underscores the need for public financing to support energy access initiatives.

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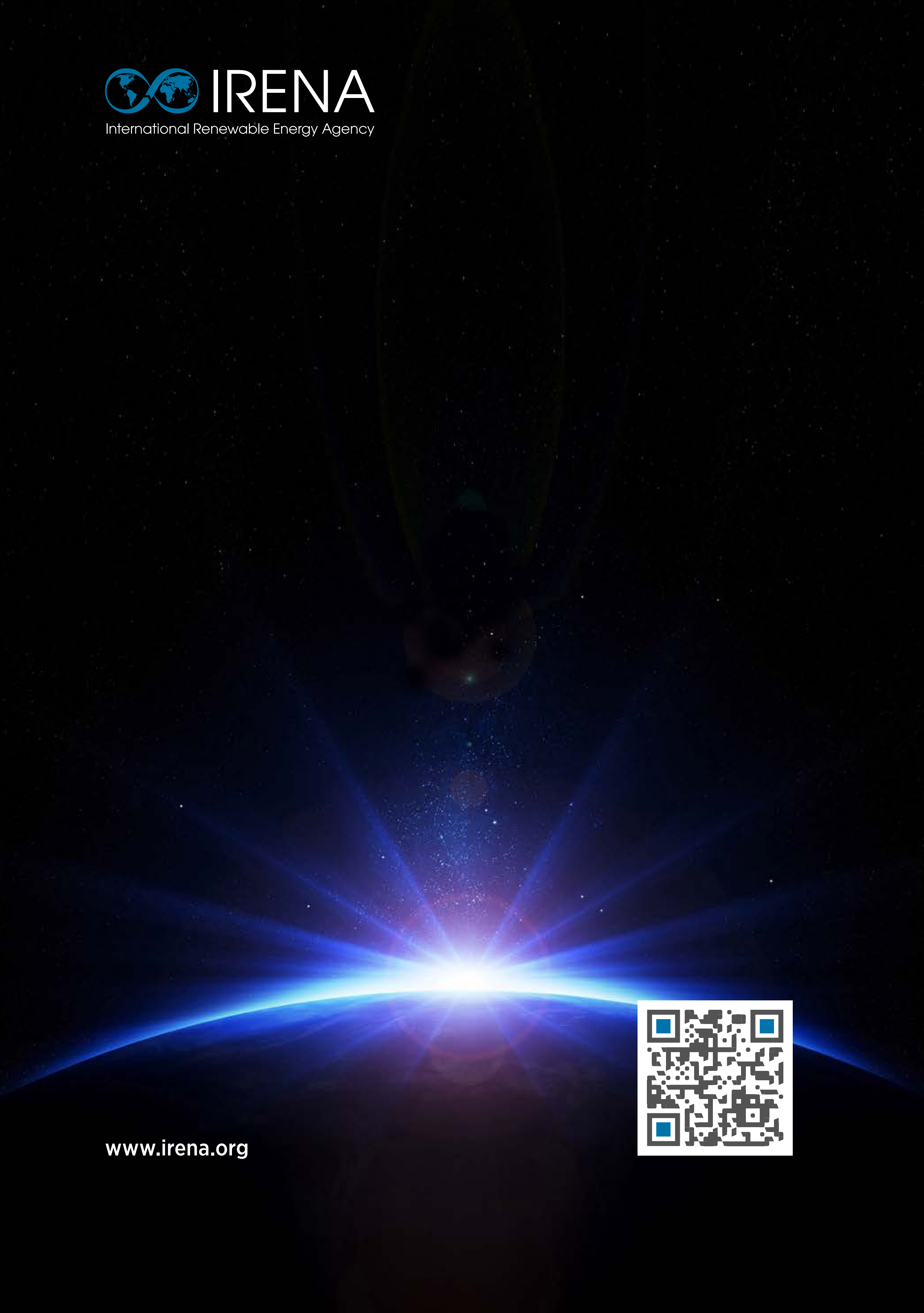

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