THE NEW **ENERGY** PARADIGM IN **A CARBON CONSTRAINED** WORLD

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LIST OF ABBREVIATIONS

AfDB	African Development Bank
AI	Artificial Intelligence
APAEC	ASEAN Plan of Action for Energy Cooperation
APEC	Asia-Pacific Economic Cooperation
APS	Announced Pledges Scenario
AR6	IPCC Sixth Assessment Report
ARC	African Risk Capacity Agency of the African Union
ARRA	American Recovery and Reinvestment Act
ASEAN	Association of South East Asian Nations
BDC	Bulk Distribution Company
BECCS	Bioenergy with Carbon Capture and Storage
BEMS	Building Energy Management Systems
BLT	Bantuan Langsung Tunai (Indonesian for Direct Cash Transfer)
Btu	British Thermal Unit
BWRX	Boiling Water Reactors
CAFE	Corporate Average Fuel Economy
CAGR	Compound Annual Growth Rate
CAT	Climate Action Tracker
CBAM	Carbon Border Adjustment Mechanism
CBDR-RC	Common But Differentiated Responsibilties and Respective Capabilities
CCGT	Combined Cycle Gas Turbines
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
CEE	Climate, Energy, Environmental (scholarly communities)
CDR	Carbon Dioxide Removal
CGE	Computable General Equilibrium
CfD	Contract for Differences
CHP	Combined Heat and Power
CH_4	Methane
CIF	Climate Investment Funds
CIPP	Comprehensive Investment and Policy Plan
CO_2	Carbon Dioxide
COP	Conference of the Parties
COP28	28th United Nations Climate Change Conference (held in Dubai, 2023)
COVID-19	Coronavirus Disease Variant 19
CPI	Consumer Price Index
CTCN	Climate Technology Centre & Network
DAC	Direct Air Capture

D&O	Directors and Officers Insurance
DER	Distributed Energy Resources
DERs	Distributed Energy Resources
DFI	Development Finance Institution
DR	Dynamic Response
DRC	Democratic Republic of Congo
ECJ	European Court of Justice
EJ	Exajoules
EMDE	Emerging Markets and Developing Economies
EPA	Environmental Protection Agency (U.S.)
EOR	Enhanced Oil Recovery
ERM	Environmental Resources Management
ESG	Environmental, Sustainable, and Governance
ESMAP	Energy Sector Management Assistance Program
ETS	Emissions Trading System
EU	European Union
EV	Electric Powered Vehicle / Electric Vehicle
EWF	Energy-Water-Food
FAO	Food and Agriculture Organization of the United Nations
FCEV	Fuel Cell Electric Vehicles
FDI	Foreign Direct Investment
F-gas	Fluorinated gas
G-20	Group of Twenty
GCF	Green Climate Fund
GCP	Global Carbon Project
GDP	Gross Domestic Product
GEF	Global Environment Facility
GHG	Greenhouse Gas
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit (German Development Cooperation)
GMO	Genetically Modified Organism
GST	Global Stocktake
GW	Gigawatt
GWP	Global Warming Potentials
H_2O	Water Vapour
HDI	Human Development Index
HFCs	Hydrofluorocarbons
HPAL	High-pressure Acid Leach
HVAC	Heating, Ventilation and Air Conditioning
ICT	Information and Communication Technology
IDCOL	Infrastructure Development Company Limited

IDR	Indonesian Rupiah
IDS	Institute of Development Studies
IEA	International Energy Agency
IFC	International Finance Corporation
IISD	International Institute for Sustainable Development
ILO	International Labour Organization
IMF	International Monetary Fund
INDC	Intended Nationally Determined Contribution
IPCC	Intergovernmental Panel on Climate Change
IoT	Internet of Things
IRA	Inflation Reduction Act
IRENA	International Renewable Energy Agency
IRMA	Initiative for Responsible Mining Assurance
ISO	International Standards Organisation
IWRM	Integrated Water Resources Management
JETP	Just Energy Transition Partnership
Ktoe	Kiloton of oil equivalent
kWh	Kilowatt-hour
LCCRD	Low-Carbon Climate-Resilient Development
LCOE	Levelised Cost of Electricity
LED	Light Emitting Diode
LNG	Liquefied Natural Gas
LT-LED	Long-term Low Emissions Development Strategy
MDB	Multilateral Development Bank
MDPI	Multidisciplinary Digital Publishing Institute
MEPS	Minimum Energy Performance Standards
MENA	Middle East and North Africa
MOMAN	Major Oil Marketers Association of Nigeria
Mt	Megaton (million metric tons)
MWH	Megawatt Hours
N_2O	Nitrous Oxide
NDC	Nationally Determined Contribution
NDCs	Nationally Determined Contributions
NO_2	Nitrogen Dioxide
NPA	National Petroleum Authority
NREL	National Renewable Energy Laboratory
NTNU	Norwegian University of Science and Technology
NZE	Net Zero Emissions
OECD	Organisation for Economic Cooperation and Development
OMC	Oil Marketing Company
OPEC	Organisation of Petroleum Exporting Countries
P2P	Peer-to-Peer
PAT	Perform, Achieve, Trade (scheme in India)

PAYG	Pay-As-You-Go
PBL	Netherlands Environmental Assessment Agency
PFCs	Perfluorocarbons
PHS	Pumped Hydro Storage
PI	Professional Indemnity
PM2.5	Particulate Matter with diameter ≤ 2.5 micrometre
PPA	Power Purchase Agreement
PV	Photovoltaic
R&D	Research and Development
RCP	Representative Concentration Pathway
REEs	Rare Earth Elements
REIPPPP	Renewable Energy Independent Power Producer Procurement Programme (South Africa)
RPS	Renewable Portfolio Standards
SAF	Sustainable Aviation Fuels
SDG	Sustainable Development Goal
SEforALL	Sustainable Energy for All (UN Initiative)
SF_6	Sulphur Hexafluoride
SGIG	Smart Grid Investment Grant
SHS	Solar Home System
SME	Steam Methane Reforming
SMR	Small Modular Reactors
SOFIA	State of World Fisheries and Aquaculture
SSP	Shared Socioeconomic Pathway
STEPS	Stated Policies Scenarios
TOR	Tema Oil Refinery
TSM	Towards Sustainable Mining
TWh	Terawatt Hours
UAE	United Arab Emirates
UHV	Ultra High Voltage
UK	United Kingdom
UN	United Nations
UNCTAD	United Nations Conference on Trade and Development
UNDP	United Nations Development Program
UNDESA	United Nations Department of Economic and Social Affairs
UNFCCC	United Nations Framework Convention on Climate Change
UNIDO	United Nations Industrial Development Organization
UNSDG	United Nations Sustainable Development Goal
USD	United States Dollar
UTE	Usinas y Trasmisiones Eléctricas (Uruguay's state-owned utility)
V2G	Vehicle-to-Grid
VAT	Value Added Tax
WEC	World Energy Council
WEF	Water-Energy-Food
WEFT	Water-Energy-Food-Technology
WHO	World Health Organization
WRI	World Resources Institute

FOREWORD

The Al-Attiyah Foundation was established with a clear and unwavering vision: to become a beacon of informed, independent, objective, and policy-relevant thought leadership in the global energy discourse. Each year, our Academic Contribution offers a detailed and rigorous platform through which that vision is articulated and expanded. In 2025, this mission feels more vital than ever, as the energy sector finds itself navigating the converging pressures of geopolitical instability, climate imperatives, and accelerated technological disruption.

This year's publication, The New Energy Paradigm in a Carbon-Constrained World, arrives at a pivotal moment. With the formal outcomes of COP29 in Baku Azerbaijan still reverberating through national and corporate policy landscapes, and with the 2030 emissions targets looming large, the global energy transition is no longer an aspiration but a rapidly materialising imperative. Across thirteen chapters, this comprehensive book brings together cutting-edge research, strategic insights, and a wide array of policy perspectives. It provides an indispensable resource for decision-makers, researchers, and industry leaders seeking to understand the deeply interwoven challenges of security, sustainability, and equity within a transformed global energy order.

The publication anchors itself in the foundational concept of the energy trilemma – the delicate and often fraught balance between energy security, environmental sustainability, and affordability. While this concept is not new, what distinguishes this contribution is its technical depth, its legal and institutional framing, and its comparative international analysis. The book dissects not only the physical infrastructure and market dynamics of energy transitions, but also the underlying regulatory, financial, and geopolitical architectures that determine their feasibility and pace.

From the intricate policy mechanisms embedded in the Paris Agreement to the latest developments in digitalisation, energy storage, and green hydrogen, this book moves beyond simple binaries of fossil versus renewable. Instead, it maps a complex terrain where innovation, governance, and justice must coexist. It recognises that climate-aligned energy futures cannot be built on a one-size-fits-all model. Whether examining sub-Saharan Africa's decentralised solar networks or China's dual-track approach to industrial growth and decarbonisation, each chapter emphasises the regional and socioeconomic specificities that must inform global pathways.

The publication also gives due attention to transitional justice and the uneven geography of climate vulnerability. Chapters on energy access, financing mechanisms, and Nationally Determined Contributions (NDCs) in developing economies underscore the need for climate finance, capacity-building, and technology transfer. These are not peripheral issues – they are essential to achieving the global targets outlined in the Paris Agreement. Without equitable transitions, we risk further deepening the divide between the Global North and South.

The Foundation's Academic Contribution 2025 is not only a record of past inquiry, but a forward-looking agenda for research, collaboration, and informed advocacy. It positions the Foundation at the heart of the global conversation on sustainable development and energy transition.

Looking ahead, the Foundation will continue to advance its role as a trusted convenor and source of knowledge in the energy and sustainability domains. Through our ongoing CEO Roundtables, international energy awards, technical bulletins, and special reports, we remain committed to knowledge-sharing that is credible, actionable, and inclusive. As we enter a decisive phase of climate and energy diplomacy, we will work with renewed vigour to support policymakers, companies, and communities in forging resilient and sustainable energy future.

I also wish to express my gratitude to our members and partners – your support continues to inspire our pursuit of excellence. It is my hope that The New Energy Paradigm in a Carbon-Constrained World will serve as a critical guide and catalyst for action as we collectively rise to meet the challenges and opportunities of a just energy transition.

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01

CHAPTER 01

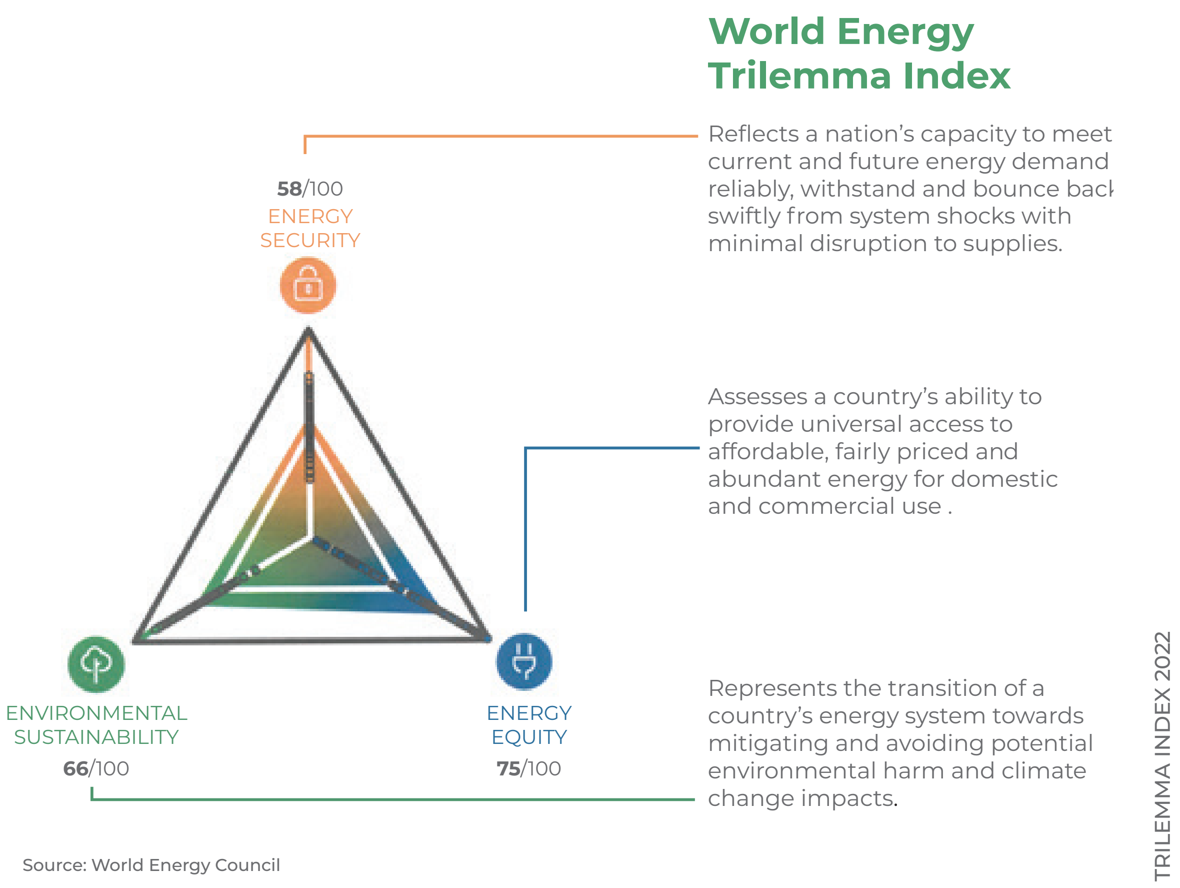
THE ENERGY TRILEMMA – SECURITY, SUSTAINABILITY, AND AFFORDABILITY

The global energy sector stands at a pivotal crossroads. In the 21st century, energy systems face intensifying demands, not only to provide reliable modern, accessible, and cost-effective energy for all, but also to embrace sustainable practices that address the growing threat of climate change. Central to this challenge is the energy trilemma: the delicate balancing act between energy security, environmental sustainability, and affordability. This chapter explores the concept of the energy trilemma, a cornerstone of both energy policy and energy law. It traces the origins of the trilemma and examines its three core pillars: ensuring secure energy supplies, maintaining affordability (either through competitive markets or regulatory intervention), and protecting the environment. Each dimension is first explored conceptually, followed by an analysis of the legislative frameworks developed to advance these objectives. The chapter also highlights how these pillars interact, sometimes synergistically, often in tension, creating a trilemma that energy law seeks to navigate. As will be shown, the energy trilemma is not merely a theoretical construct but a foundational concept that shapes energy governance at international, regional, and national levels.

Achieving an optimal balance between these three pillars is a complex task, as improving one aspect can sometimes compromise another. For example, prioritising sustainability by shifting to renewable energy sources might lead to higher costs (affordability) or intermittency issues (security). Indeed, some experts will claim that this shift is already impacting costs. The phrase was coined and popularised by the World Energy Council (WEC). It led to the production of their Trilemma Index which summarises a country's ability to balance the three arms of the trilemma. ▸

Energy security refers to the uninterrupted availability of energy at an affordable price. It encompasses short-term resilience to supply shocks and long-term access to reliable and diversified energy sources. Geopolitical risks are an important feature of energy security. Heavy reliance on energy supply chains involving politically unstable regions exposes countries to supply disruptions. The Russia-Ukraine conflict highlighted Europe's vulnerability due to its partial dependence on Russia for gas. The condition of the existing energy infrastructure and the availability of the resources are also important facets of energy security. A fragile infrastructure, whether pipeline, electrical transmission network, or plant, can compromise energy supply and so endanger energy security. Fossil fuel reserves are finite, leading to concerns about future availability and hence a concern about the long-term security of the supply of energy.

Security of Supply is fundamentally a national concern, as market forces alone are unlikely to drive diversification beyond the most cost-effective options. While diversification can enhance energy security and longer term cost advantages, it inevitably comes at a price in the short term, since alternatives to the cheapest sources must be used. Governments can play a critical role in promoting a balanced mix of domestic and imported energy. While importing energy can be more affordable, it carries the risk of disruption due to geopolitical, technical, or economic factors. Domestic renewable sources can reduce reliance on imported fossil fuels, yet they may be subject to intermittency and seasonal variability. To bolster energy security, the European Union (EU) has introduced mandatory requirements for member states to maintain strategic reserves. These include 1,047 TWh of oil and, more recently, 1,025 TWh of natural gas in storage. The tension between these objectives is particularly evident during energy crises. "The 2021–2022 global energy crisis, driven by COVID-19 recovery and geopolitical tensions (notably the Russia-Ukraine war), highlighted how governments prioritise security and affordability during shocks. Some countries reverted to coal and delayed renewable projects.



Source: World Energy Council

Figure 1: World Energy Trilemma Diagram

Energy sustainability was underscored in 1987 when the United Nations Brundtland Commission defined sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs." Today, nearly 140 countries are striving to meet development goals, but with the mounting threat of climate change, concrete efforts are essential to ensure that present-day progress does not come at the expense of future generations.

The UN's Sustainable Development Goals form the framework for improving the lives of populations around the world and mitigating the hazardous man-made effects of climate change. Sustainable Development Goal 13, more commonly known as SDG 13: Climate Action, calls for integrating measures to prevent climate change within development frameworks. SDG 14: Life Below Water, and SDG 15: Life on Land, also call for more sustainable practices in using the earth's natural resources.

Despite such initiatives there are major hurdles to their implementation. Fossil fuel combustion accounts for over 70% of global GHG emissions and coal and oil extraction impact air and water quality; hydropower dams and biofuels can affect ecosystems and cause loss of biodiversity.

Solar, wind, hydro, and geothermal power can be sustainable solutions providing clean alternatives but often at the cost and some loss of security of supply. One key strategy for addressing this issue is to enhance the circularity of the economy (reuse, repair, refurbish, remanufacture, recycle). Where that is not possible or after the implementation of such type of climate and sustainability action, the second option is, for the satisfaction of the core human needs, to disrupt the use of products and services that are energy or material intense and replace them by alternative products and services that are less energy and or material intense. The third option after implementation of these first two most impactful climate and sustainability action for a satisfaction of a need, is to improve the efficiency of use of products and services. Only once the opportunities to undertake these types of climate and sustainability actions are exhausted, then for existing products or services, improve the energy and material efficiency—using less energy and material to achieve the same outcomes. Innovations such as compact, complete, walkable and transit rich cities, smart buildings, energy-efficient appliances, and cleaner transport systems help reduce overall demand and contribute to sustainability. Advances in technology continue to enhance energy efficiency, making it a critical component of the transition to a low-carbon future.

Sustainability means meeting the needs of the present without compromising future generations.

Sustainable solutions require reductions in both carbon dioxide (CO_2) and methane (CH_4) emissions. Here, Carbon Capture and Storage (CCS) mitigates emissions from unavoidable fossil fuel use. However, these solutions are currently costly. The move to a hydrogen-based economy (i.e. "burning hydrogen rather than carbon") shows promise but is also prohibitively expensive.

Energy Affordability (and Equity) is the final pillar of the trilemma. Affordability refers to the ability of consumers to pay for energy services, while equity pertains to fair access across populations, including rural and low-income communities. Globally, over 700 million people lack access to electricity predominantly in Sub-Saharan Africa and parts of Asia. Energy poverty limits access to education, healthcare, and economic opportunities.

Trilemma Case Studies

Europe's Energy Transition

Europe's transition to green energy has produced mixed results. In Germany, for example, the Energiewende, a national policy aimed at phasing out nuclear power and fossil fuels in favour of renewables, has led to major investments in clean energy. However, the country has also experienced rising energy prices and supply instability, particularly during disruptions to gas imports. The rapid phase-out of nuclear energy now appears to have been a hasty decision. This has caused a renewal of coal and lignite imports into Germany and a crisis in Germany's manufacturing industry due to high energy costs. This underscores the need for balanced and robust planning.

China's Dual Challenge

China leads in solar and wind deployment but remains the largest coal consumer in the world. Its trilemma lies in phasing out coal without jeopardising economic growth or energy access, especially in industrial regions.

Sub-Saharan Africa

Access remains the primary concern. Solutions like solar home systems and pay-as-you-go models are gaining traction. International financing plays a vital role in expanding infrastructure without burdening governments.

Energy Markets and Carbon Pricing

Liberalised energy markets increase efficiency, while carbon pricing internalises environmental costs, guiding investments toward cleaner energy.

What are the Solutions to the Trilemma?

Achieving equilibrium among the three pillars requires holistic policy frameworks, sector specific interventions, innovation, and international cooperation. Some key strategies include:

1) **Global Cooperation and Multilateral frameworks:** The Paris Agreement, International Energy Agency (IEA) initiatives, and UN Sustainable Development Goals (SDG 7) can foster knowledge-sharing, funding, and technology transfer.

2) **Diversification and Integration:** Each intervention should combine electrification, diversifying energy sources—across renewables, nuclear, natural gas, and energy storage— energy-efficiency upgrades, and circular-economy practices to enhances both security and sustainability. Regional grid integration allows countries to trade electricity and stabilise supply (e.g., the European interconnector system). At the industrial level, Recognise the specificity of subsectors and develop dedicated intervention for cement, steel, glass, chemicals, and other high-emission industries. Policymaking should prioritise coordinated portfolios of measures that address each unique energy need and emissions profile.

3) **Investment in Technology:** Battery storage, smart grids, and demand response systems can mitigate intermittency and boost renewable reliability. Emerging technologies like green hydrogen and advanced nuclear (e.g., small modular reactors) hold promise for sustainable baseload power. However, current costs will inevitably rise.

4) **Access to products and services and energy:** Shifting from combustion car to EV is good but we need to ask the question why do we need car at the first place? Use digital technology to access products and services without the need for mobility (e.g. online municipality services, virtual learning where possible). Where this is not possible disrupt partly motorised transportation by using GIS, GPS and remote sensing for land use planning and site selection in cities to build a 15 minutes city, where most of the products and services are available at walking or biking distance. Then, where motorised transportation cannot be disrupted, prioritise large-scale rail upgrades, bus rapid transit corridors, and urban tram expansions. Joint transport-land use planning, will speed up necessary infrastructure

investments. Enhanced public transit networks will reduce reliance on private cars, cutting transportation emissions and alleviating urban congestion. Where personal car cannot be avoided, promote the shift to EV.

Introduce standards, incentives instruments and regulatory frameworks to increase the use of clean fuels (e.g. biofuel blends) in shipping and aviation. The standards can provide blending requirements for sectoral transportation fuels; the incentive instrument can offer tax credits or direct compensation to airlines that integrate sustainable aviation fuels. Where the blending requirement are not met, penalties can be determined by the regulatory framework. This will ensure that biofuels help decarbonise hard-to abate transport modes. The biofuel blend requirements should take into account the availability of land for other form of land use including for renewable electricity generation.

5) **Nutrition, the agri-food system and energy:** Leverage systemic innovations that enable dietary shifts (with alternative ways to satisfy the need for protein), large-scale organic or regenerative farming and local food resilience with urban rooftop farming and vertical agriculture. Incentives crop diversification, agroforestry, and reduced meat consumption. Policy and Market Reforms: Carbon pricing internalises environmental costs, incentivising clean energy. Subsidy reforms can redirect funds from fossil fuels to renewable support. Energy efficiency standards reduce demand, easing affordability and sustainability pressures.

6) **Just Transition and Social Equity:** Policies must also consider economic and social impacts—protecting asset owners and workers in value chains that can be affected from stranded asset or stranded people as well as vulnerable populations from energy poverty. The policies should promote innovative alternatives that can accommodate the repurposing of assets to avoid stranded assets and financial failures as well as the repurposing of skills to avoid stranded people and social failures. Where such repurposing is not possible, reskilling programmes can help fossil fuel workers transition to clean energy jobs. Community energy projects and inclusive decision-making enhance social acceptance. Decentralised systems (e.g., rooftop solar, micro-grids) empower local communities and enhance resilience. Digital technologies (IoT, AI) optimise energy use and grid management, improving efficiency.

7) **Electrification and Sector Coupling:** Electrifying transport, heating, and industry increases demand but creates synergies—especially when powered by renewables. Coupling energy sectors can enhance flexibility (e.g., using excess wind power for green hydrogen production).

Regional Approaches to the Energy Trilemma

Europe: Sustainability First

Focus: Reducing carbon emissions and increasing renewable energy adoption.

Policies: The EU's Green Deal aims for carbon neutrality by 2050, with strong policies on wind, solar, and hydrogen.

Challenges: Balancing sustainability with energy security, as reliance on Russian gas has led to volatility in affordability.

Example: Germany's Energiewende (energy transition) promotes renewables but has faced high electricity prices and reliance on coal/nuclear phase-out.

United States: Market-Driven Balance

Focus: A mix of affordability and security, with sustainability driven by state-level policies.

Policies: Energy mix includes renewables, natural gas, and nuclear, with a growing emphasis on green tech (e.g., Inflation Reduction Act incentives).

Challenges: Balancing fossil fuel interests with clean energy investments.

Example: Texas leads in wind power but still relies on fossil fuels for grid stability.

China: Security & Affordability First

Focus: Energy security and affordability to sustain economic growth.

Policies: Heavy investment in renewables (largest solar & wind producer) but still reliant on coal for baseload power.

Challenges: Decarbonisation while meeting rising energy demand.

Example: Expanding nuclear and hydro power alongside solar and coal capacity.

Middle East: Security & Affordability, Emerging Sustainability

Focus: Historically fossil fuel-based, now expanding renewables.

Policies: Investments in solar (e.g., UAE's Noor Abu Dhabi solar plant) and hydrogen projects.

Challenges: Diversifying energy while maintaining economic reliance on oil exports.

Example: Saudi Arabia's Vision 2030 aims to shift towards renewables while keeping oil dominance.

Organisational Approaches to the Energy Trilemma

The WEC publishes an annual Energy Trilemma Index, ranking countries on their energy security, equity (affordability), and sustainability.

The IEA advocates for balanced energy transitions, ensuring secure and affordable energy while reducing emissions.

Oil and gas companies (e.g., Shell, BP, Aramco) are diversifying their portfolios by investing in renewables, carbon capture, and hydrogen, while still maintaining oil and gas production.

Renewable energy companies (e.g., Tesla, Ørsted, Iberdrola) are prioritising sustainability while working on energy storage and grid stability to enhance security as well as cost reduction to ensure energy equity.

> Energy law has evolved from state monopolies, to liberalised markets, to today's focus on climate protection.

Energy Law Has Played a Role in Trying to Tackle the Trilemma

Energy law is a normative field of law, heavily influenced and shaped by changing political priorities. Three different trends or phases in its development may be distinguished. In the first phase, which lasted until the end of the 1980s, legislators mainly focused on ensuring the security of energy supplies through the use of monopolies. There was broad acceptance of heavy state involvement in the energy sector, owing to the fundamental role played by energy in the daily lives of a country's population. The defining moment of this phase was the oil crisis of 1973, which affected both energy law and energy policy around the globe. Following the oil crisis in the EU, the European Court of Justice (ECJ) in the Campus Oil case, held that it held the sole right of interpretation of EU Treaties. The case demonstrated for the first time an awareness that a steady flow of energy in modern societies can literally become a matter of life and death (e.g. energy supplies to hospitals). In the United States, the oil crisis resulted in a push for the internationalisation of energy policy, resulting in the creation of the IEA, with the explicit aim of securing energy supplies. Energy was considered as something that needed to be secured for consumer nations. While this line of thought continues to be relevant (and still is part of modern energy law today), over the course of the 1990s a second issue emerged, one given equal weight – energy prices. The perception during this second phase was that existing monopolies were inefficient, leading to higher energy prices, and that these monopolies needed to be broken up, energy markets liberalised, and the competition introduced into the market. The tool used to achieve this aim was energy law. From the tail end of the 1990s onwards, legal frameworks governing energy markets were re-designed to allow for market liberalisation, opening a significant number of markets up to competition. As a result, consumers today can choose from a range of hundreds of energy suppliers – there is far more choice available than was previously the case. While final customers may choose a supplier based solely on price, they may also be motivated by security of supply concerns (ensuring the lights stay on), and increasingly, the environmental impact of the energy source.

The third trend relates to environmental protection and concerns over climate change. The 1970s saw an increase in the awareness (in some countries and regions) of the correlation between the environment, the climate, and energy. From a legal perspective, this third phase is mainly addressed through national laws, though regional and even international law are more and more playing substantial roles. A growth in environmental laws may be perceived from the late 1970s onwards, with these increasingly impacting the energy sector (for instance, environmental impact assessments for power plants, and protection of certain species and habitats in area with oil or gas potential). At an international level, the adoption of the United Nations Framework Convention on Climate Change in 1992 was a landmark moment in the consideration of climate issues. In the early 2000s, governments around the globe started to alter their energy subsidies, re-structuring them to substantially boost renewable energy production. The regulation of renewable energy is an example of energy law serving environmental and climate protection purposes, while aiming to ensure other goals of the trilemma, such as energy security. Developments in recent years (in a world where renewable energy production is increasingly being integrated into energy markets and subsidies are being reduced) indicate that regulation of the sector is being dominated by another aspect of the energy 'trilemma' – markets and economic development. This showcases the interplay of the three main components of the energy trilemma. Examples of this in the EU are the methane emission regulations and the Carbon Border Adjustment Mechanism (CBAM). CBAM is a regulatory framework established by the European Union to address carbon leakage, which occurs when companies relocate production to countries with less stringent climate policies. By imposing a carbon tax on imported goods, CBAM ensures that penalty related to their carbon footprint is reflected in the price of these goods, promoting fair competition between EU and non-EU producers.

Key Strategies for Addressing the Trilemma

Some approaches and technologies have emerged as more suitable in tackling the Trilemma:

Energy Storage & Grid Modernisation – Investing in battery storage, smart grids, and AI-driven energy management.

Hydrogen & Carbon Capture – Balancing sustainability with security using emerging technologies.

Diversification of Energy Sources – A mix of renewables, nuclear, and fossil fuels with carbon management.

Regional Cooperation – Cross-border energy trade (e.g., EU's interconnected grids) enhances security and affordability.

Digital grids and battery storage are critical to balancing intermittent renewables and demand management. These technologies can significantly reduce trade-offs between security and sustainability.

A daring mindset and a moonshot thinking facilitate goals setting not on the basis of what is perceived as possible but based on what is needed.

Innovative financial instruments such as integrated green bond and carbon market can turn the carbon finance which is currently an ex-post reward into an upfront enabler.

Innovative business models such as the Pay-as-you-go facilitate access to energy for the underserved.

Conclusion

The energy trilemma is not a zero-sum game. While tensions among security, sustainability, and affordability are inevitable, they are not insurmountable. With holistic analysis, tailored policies, technological innovation, innovative financial instruments, innovative business models and international collaboration, it is possible to forge a win-win path toward a just, clean, and reliable energy future.

Ultimately, the way to break the trilemma will be by integrating technological progress, innovative policies, innovative financial instruments, innovative business models and innovative cooperative approaches because radical collaboration will be needed.

Crises like pandemics and conflicts may momentarily disrupt advancement, but they also underscore the need for resilient and sustainable energy systems. As the global community navigates this intricate landscape, success will depend on aligning economic development with environmental stewardship and social equity.

However, the energy trilemma is not just an engineering problem—it is a moral and political one, with far-reaching implications for future generations. The world stands at an inflection point. Today's energy decisions will determine whether future generations inherit a liveable planet or a climate burden.

02

CHAPTER 02

THE SCIENCE OF CLIMATE CHANGE AND ENERGY'S ROLE

Global warming, the long-term rise in Earth's average surface temperature, is one of the most pressing challenges of our time. It is primarily driven by human activities that increase the concentration of greenhouse gases (GHGs) in the atmosphere. Understanding the scientific principles underlying global warming is essential for developing effective mitigation and adaptation strategies.

Energy systems play a central role, as they are the largest source of anthropogenic greenhouse gas emissions. Understanding the relationship between energy production, consumption, and emissions is critical for identifying pathways to a sustainable and low-carbon future. Industrialisation has been a key driver of economic development and modernisation across the globe. However, it has also significantly increased energy consumption and greenhouse gas emissions, contributing to anthropogenic climate change.

To limit the most dangerous impacts of climate change, the international community has established long-term climate goals, most notably through the Paris Agreement. These include limiting global temperature rise to well below 2°C, preferably to 1.5°C above pre-industrial levels. The concept of a carbon budget provides a critical framework for understanding how much carbon dioxide (CO_2) can still be emitted while limiting global warming to the internationally agreed targets.

This chapter explores the physical basis of global warming, focusing on the greenhouse effect, the role of key GHGs, radiative forcing, and climate feedback mechanisms. It also outlines the empirical evidence for anthropogenic climate change. The chapter also examines the major sources of energy, their emissions profiles, and the impact of current energy infrastructure on the climate. It explores the historical and contemporary links between industrialisation, energy use, and climate change. It highlights the evolution of industrial energy demand, sectoral contributions to emissions, and the challenges of decarbonising industrial systems.

The chapter further explores the scientific basis of the concept of carbon budget and discusses how various energy systems affect emissions trajectories. It concludes a discussion of the science and policy behind long-term climate targets, the rise of net-zero commitments, and their implications for national strategies, energy systems, and international collaboration. ▸

The Fundamental Science Behind Global Warming

The Earth's Energy Balance and the Greenhouse Effect

The Earth receives energy from the sun in the form of solar radiation and emits energy back into space in the form of infrared radiation. Certain gases in the atmosphere, such as CO_2, methane (CH_4), Nitrous oxide (N_2O), and water vapour (H_2O), trap some of the outgoing infrared radiation. This natural greenhouse effect keeps Earth's surface about 33°C warmer than it would be without an atmosphere. For Earth's temperature to remain stable, the incoming solar energy must be balanced by the outgoing thermal radiation. This process, caused by greenhouse effect, is natural and necessary to support life.

However, human activities have increased concentrations of GHGs, CO_2, CH_4, and N_2O in the atmosphere (see Figure 1). In addition to these three primary GHGs, the six anthropogenic GHGs also include: Hydrofluorocarbons (HFCs); Perfluorocarbons (PFCs); and Sulphur Hexafluoride (SF_6). The human induced increases of these anthropogenic GHG emissions blanket the Earth, trapping the sun's heat (greenhouse effect). This leads to global warming and climate change. Global temperatures are rising at the fastest rate observed in the modern instrumental record. Warmer temperatures over time are changing weather patterns and disrupting the usual balance of nature.

The eight major sources of man-made GHG emissions include: power generation; waste disposal and treatment; land use and biomass burning; residential, commercial and other sources; fossil fuel retrieval, processing and distribution; agricultural byproducts; transportation fuels; and industrial processes (Figure 2).

The top panel shows the sum over all man-made GHGs, weighted by their global warming potential over the next 100 years. This consists of 72% CO_2, 18% CH_4, 9% nitrous oxide (N_2O) and 1% other gases.

Lower panels show comparable information for each of these three primary GHGs, with the same colouring of sectors as used in the top chart. Segments with less than 1% fraction are not labelled.

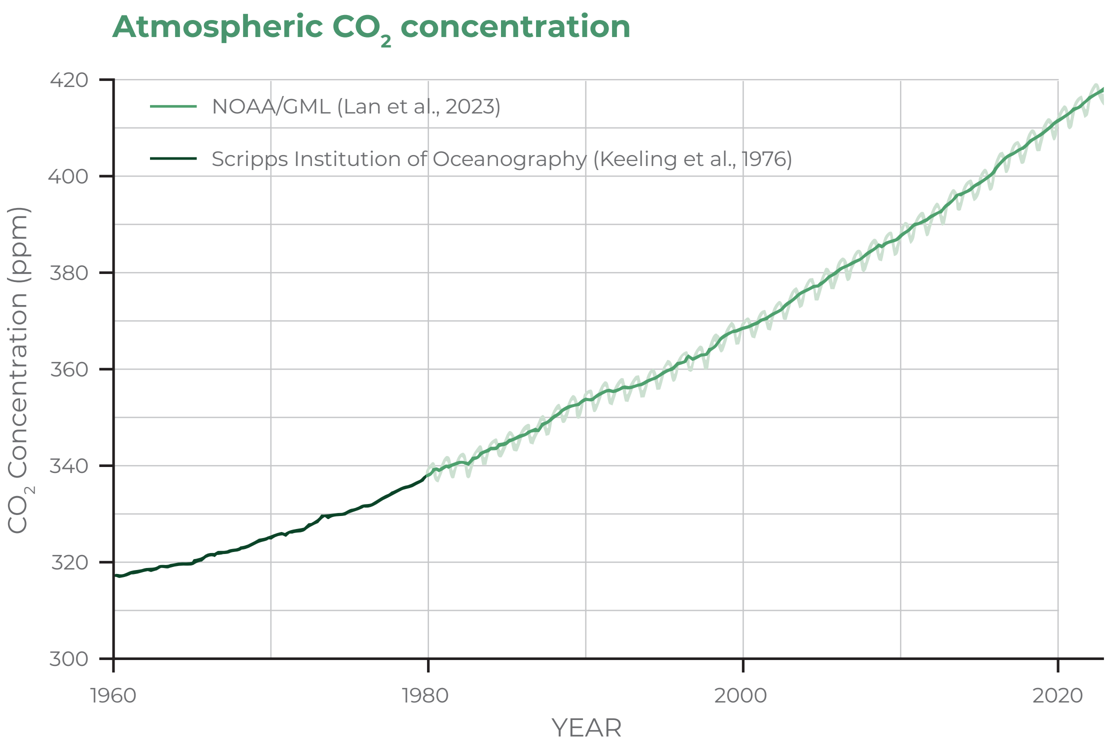


Figure 1: Global Atmospheric CO_2 Concentration (1959–2023). (Source: https://commons.wikimedia.org/wiki/File:Surface_average_atmospheric_CO2_concentration_%28ppm%29_over_time.png.)

Annual Greenhouse Gas Emissions By Sector

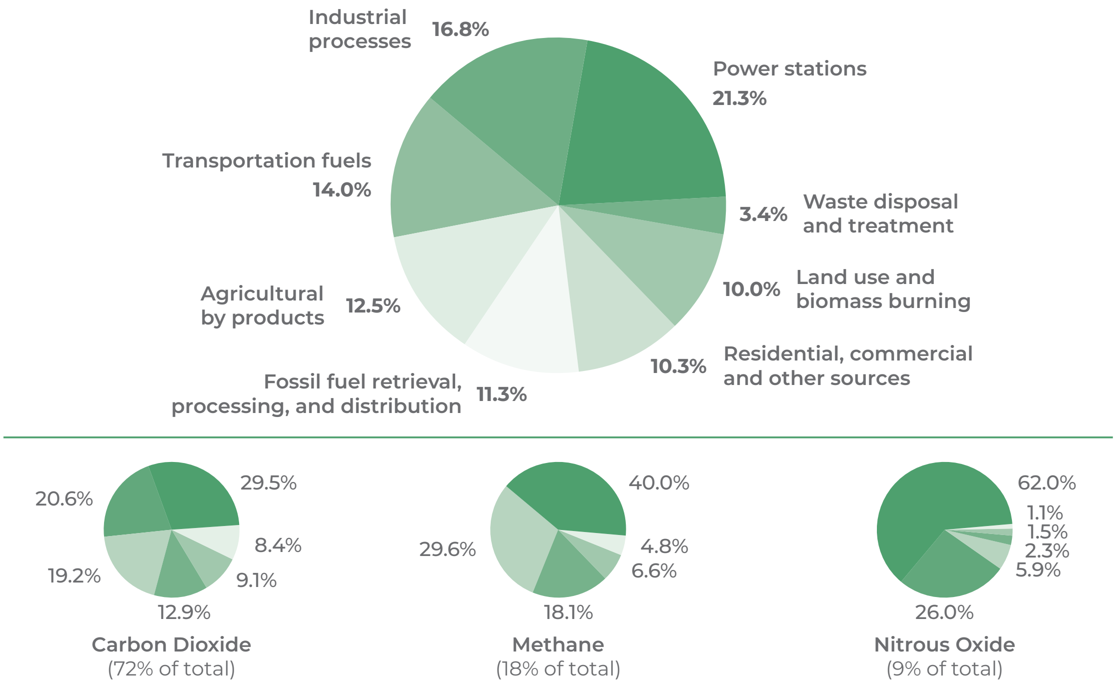


Figure 2: Relative Fraction of Anthropogenic Greenhouse Gases Emissions From Eight Categories of Sources (Sources: https://www.researchgate.net/figure/Annual-greenhouse-gas-emissions-by-sector-and-carbon-dioxide-contribution_fig1_348214397)

Global Warming Potential of Greenhouse Gases

Different GHGs can have different effects on the Earth's warming. The two ways in which these gases differ from each other are their ability to absorb energy (their "radiative efficiency"), and how long they stay in the atmosphere (also known as their "lifetime"). They can remain in the atmosphere for varying amounts of time, ranging from a few years to thousands of years. In addition, some gases are more effective than others at making the planet warmer. Global Warming Potential (GWP) is a measure of climate impacts based on how long each greenhouse gas remains in the atmosphere and how strongly it absorbs energy.

Since 1990, the Intergovernmental Panel on Climate Change (IPCC) has used GWP as a standard metric to compare the climate impacts of different greenhouse gases. GWP quantifies how much energy the emission of one tonne of a gas will absorb over a specified time period, relative to one tonne of CO_2. A higher GWP indicates a greater warming effect compared to CO_2. The most commonly used time horizon for GWPs is 100 years. This metric provides a unified basis for summing emissions across gases—facilitating national GHG inventories—and enables policymakers to assess and compare mitigation options across sectors and gas types.

CO_2, by definition, has a GWP of one, regardless of the time used, because it is the gas being used as the reference. However, CO_2 remains in the climate system for a long time, causing increases in atmospheric concentrations that last thousands of years. Methane (CH_4) is estimated to have a GWP of 27 to 30 over 100 years. CH_4 emitted today lasts about a decade on average, which is much less than CO_2. However, CH_4 also absorbs much more energy than CO_2. The net effect of the shorter lifetime and higher energy absorption is reflected in the GWP. Nitrous Oxide (N_2O) has a GWP 273 times that of CO_2 for a 100-year timescale. N_2O emitted today remains in the atmosphere for more than 100 years, on average. Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6) are sometimes called high-GWP gases because, for a given amount of mass, they trap substantially more heat than CO_2. The GWPs for these gases can be in the thousands or tens of thousands. Once emitted, HFCs, PFCs, and SF_6 persist in the atmosphere for hundreds or thousands of years.

Empirical Evidence of Global Warming

Scientists have determined that when all human and natural factors are considered, Earth's climate balance has been altered towards warming, with the biggest contributor being increases in CO_2. The atmospheric concentrations of CO_2, methane, and nitrous oxide have increased significantly since the Industrial Revolution began. In the case of CO_2, the average concentration measured at the Mauna Loa Observatory in Hawaii has risen from 316 parts per million (ppm) in 1959 (the first full year of data available) to more than 411 ppm in 2019. The same rates of increase have since been recorded at numerous other stations worldwide. Since pre-industrial times, the atmospheric concentration of CO_2 has increased by over 40%, methane has increased by more than 150%, and nitrous oxide has increased by roughly 20%.

Many other impacts associated with the warming trend have become evident in recent years. Arctic summer ice cover has shrunk dramatically. The heat content of the ocean has increased. Global average sea level has risen by approximately 16 cm since 1901, due both to the expansion of warmer ocean water and to the addition of melted waters from glaciers and ice sheets on land. Warming and precipitation changes are altering the geographical ranges of many plant and animal species and the timing of their life cycles.

Climate models confirm recent warming is due to human activities. The Intergovernmental Panel on Climate Change (IPCC) affirms that natural factors alone cannot account for the observed trends. Rigorous analysis of all data and lines of evidence shows that most of the observed global warming over the past 50 years cannot be explained by natural causes and instead requires a significant role for the influence of human activities.

The key signs of climate change could be summarised as follows:

- Global temperatures are increasing
- Ocean temperatures are increasing
- Soil temperatures are increasing
- Oceans are more acidic
- Humidity is increasing
- Arctic sea ice extent is diminishing
- Springtime snow cover is going down
- Glaciers are shrinking
- Forest fire season is longer
- The seas are rising
- The weather is becoming more extreme
- The ranges of plants and animals are shifting

The Role of Energy Systems in Climate Change

Industrialisation and Energy Demand

The development of energy is an essential component of industrialisation. Economic growth and technological advancement are driven by the availability and affordability of energy sources. Global energy demand has risen steadily with economic growth and population expansion. According to the IEA, fossil fuels continue to dominate global energy supply, accounting for about 80% of primary energy consumption as of 2023.

Historically, industrial revolutions have promoted the advent and growth of the consumption of energy sources, such as coal, oil, and natural gas, and established an energy consumption structure dominated by fossil fuels. As urbanisation and industrialisation continue to increase, especially in emerging economies, there are questions as to how these two attributes of modernisation will impact energy use.

This is of particular concern in emerging economies where urbanisation and industrialisation are growing rapidly. Between 1980 and 2008, urbanisation in Brazil rose from 67.4 percent to 85.6 percent while urbanisation in China more than doubled from 19.6 percent to 43.1 percent. If urbanisation and industrialisation have a significant impact on energy demand, this will have implications for sustainable development and climate change. For example, if urbanisation and industrialisation increase energy usage, then forecasting models that exclude these socioeconomic variables may seriously underestimate future energy needs with the result that sustainable development goals will be more difficult to achieve.

The connection between energy consumption and sustainable development is particularly evident if one considers the impact that energy consumption has on GHG emissions. Since 61.4 percent of global GHG emissions come from the production, distribution, and use of energy, any serious attempt to control greenhouse gas emissions will have to focus on reducing fossil fuel combustion and increasing renewable energy consumption.

High-income countries underwent early industrialisation phases, resulting in high cumulative emissions. Emerging economies such as China and India have more recently industrialised and now contribute significantly to global emissions due to rapid industrial growth. Decoupling industrial growth from emissions remains a major challenge for climate policy. The co-benefits that disruption of carbon intensive value chain and industrial decarbonisation could offer, such as improved air quality, innovation, and job creation in green technology sectors, may involve trade-offs like economic restructuring, employment shifts, and the need for just-transition frameworks. Climate policy should take cognisance of such trade-offs.

Carbon Budget and How Energy Systems Impact Emissions

The carbon budget refers to the cumulative amount of CO_2 that can be emitted while still having a likely chance of limiting global temperature rise to a specific threshold. Since the industrial revolution, over 2,400 $GtCO_2$ have been emitted by human activity, with fossil fuel combustion and land use changes as the primary sources. As of 2020, approximately 85% of the 1.5°C carbon budget had been used. Emissions since then have further reduced the remaining budget. According to the IPCC Sixth Assessment Report (AR6), released in 2021, for a 50% probability of limiting warming to 1.5°C, the remaining carbon budget from 2020 onwards is approximately 500 $GtCO_2$. Current global CO_2 emissions are over 36 $GtCO_2$ per year, meaning the 1.5°C carbon budget could be exhausted within the next decade without significant emission reductions.

Most of the observed global warming over the past 50 years cannot be explained by natural causes — it requires a significant role for human activities.

Figure 3 shows the ten countries with the largest share of the world's historical emissions, based on cumulative emissions from fossil fuels and industry since 1750. The United States has contributed the most, accounting for almost one quarter. This is followed by China and Russia.

To extend the carbon budget, carbon dioxide removal (CDR) methods like afforestation, direct air capture, and bioenergy with carbon capture and storage (BECCS) are being explored. However, the IPCC Sixth Assessment Report (AR6), pointed out that these technologies are still nascent

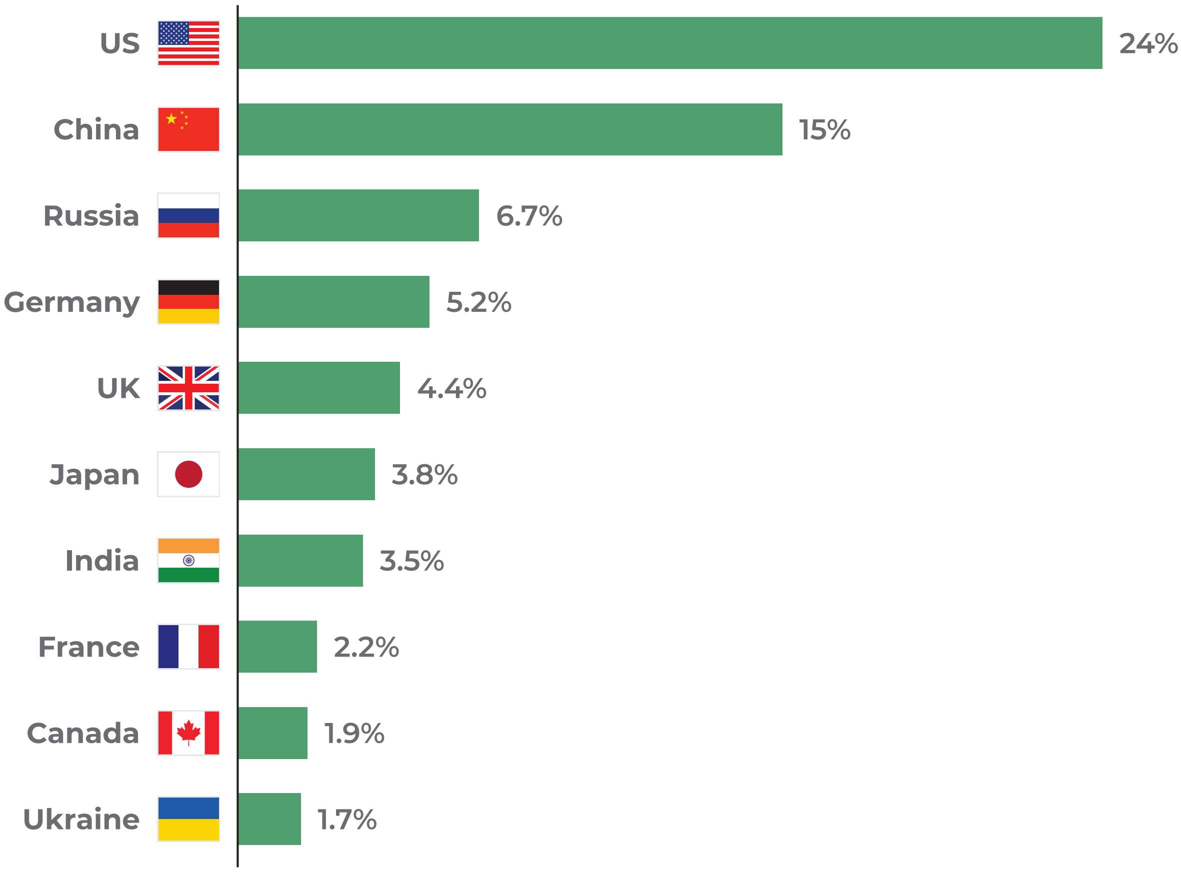


Figure 3: Historical CO_2 Emissions by Top 10 Countries. (Source: https://ourworldindata.org/data-insights/which-countries-have-contributed-the-most-to-historical-co-emissions#:~:text=The%20chart%20shows%20the%20ten,followed%20by%20China%20and%20Russia.

and must not replace near-term emissions reductions and avoidance.

Since high-income countries are responsible for the majority of historical emissions, while low-income countries often face the harshest climate impacts, a fair consideration of carbon budgeting should take into historical responsibility, capability to reduce emissions, and development needs of emerging economies. This equitable consideration has bedevilled climate change diplomacy and has been vocally contested in the climate change multilateral processes. However, this issue continues to underline the importance of climate justice in energy transition policies.

Two critically important aspects that have been overlooked by the climate change multilateral processes as well as by most of the climate experts:

1. The carbon budget should not be allocated to sectors (such as steel, cement, chemicals…) but to needs, mainly the core human needs (nutrition and dietary related health, shelter, access to products and services, leisure, clothing, education). This is fairer, otherwise, a country that does not have industries will not have part of the carbon budget
2. We need to separate the allocation of the carbon budget to needs and countries which should be done with the view to minimise the cost of addressing climate change (and is a technical issue) from the issue of who will pay to keep human activities in a country within the carbon budget (which is a political issue and should consider the principle of CBDR and capability).

Avoiding carbon budget overshoot will require a host of actions, including rapid deployment of renewables and electrification, phasing out coal and reducing oil and gas, strengthening efficiency standards and demand management, and financing green infrastructure and innovation. The IEA and IPCC analysis indicate that all scenarios consistent with 1.5°C require deep energy sector transformation by 2030.

Long-term climate goals and the role of net-zero commitments

The Rationale Behind Long-term Climate Goals

Long-term climate goals create a vision driven approach to climate action which starts from the future we want to build and uses a back-casting normative scenario to turn that future into actions we should undertake now. The main objective of the Paris Agreement is to hold the increase in the global average temperature rise to well below 2°C above pre-industrial levels. This should be achieved in conjunction with efforts to limit this temperature increase to 1.5°C, significantly reducing the risks and impacts of climate change.

To achieve these goals, the Paris Agreement outlines a number of tasks for the signatories. First, global peaking of GHG emissions must occur as soon as possible, with deep and rapid reductions thereafter in accordance with the best available science. Second, countries must achieve a balance between human-caused GHG emissions by sources and removals by sinks of those GHGs in the second half of the century. In plain English, that means getting to global net zero by 2050.

Long-term strategies (also called "long-term low GHG emissions development strategies," "LTS" or "LT-LEDs") are central to achieving net-zero emissions, limiting warming and preventing some of the worst impacts of climate change. Countries can use these strategies to set out long-term goals for climate and development and direct the short-term decision-making that is needed to achieve net-zero emissions and climate-resilient economies.

Rise of Net-Zero Commitments

As of 2024, over 140 countries, covering more than 90% of global GDP, have announced net-zero targets. These range in scope and timeline, with most countries such as the European Union (EU), United Kingdom (UK), Norway, Canada, New Zealand, Costa Rica, the United States, the UAE, Brazil, and Australia, making net-zero commitments for 2050. Iceland sets a target date of 2040 to achieve net-zero. Other countries like Bahrain (2060), Saudi Arabia (2060), China (2060), India (2070), and Russia (2060), set net-zero targets beyond 2050.

A growing number of major corporations have also made such commitments,

Table 1: List of the Countries with Net-Zero Targets Beyond 2050

Country	Net-zero Target Year	Type of Target	Share of Global GHG Emission
Bahrain	2060	Political Pledge	0.1%
China	2060	Policy	23.9%
India	2070	Political Pledge	6.8%
Russia	2060	Political Pledge	4.1%
Saudi Arabia	2060	Political Pledge	1.3%
Turkey	2053	Political Pledge	1.0%
Nigeria	2060	Political Pledge	0.7%
Kazakhstan	2060	Political Pledge	0.6%
Ukraine	2060	Political Pledge	0.5%

including oil companies (Shell, BP, Equinor, Total and others), and airlines (the Oneworld alliance, including Qatar Airways). Elsewhere, Amazon is aiming to be net-zero by 2040 and Microsoft is working towards being ‘carbon-negative’ by 2030 and offsetting all its historic emissions by 2050. Google claims to have been ‘carbon-neutral’ since 2007 and plans to be ‘carbon-free’ by 2030.

Accountability, transparent tracking of emissions, and monitoring of progress are vital for the attainment of the net-zero targets. There are several established frameworks for monitoring and accountability, including the five-yearly Global Stocktake (GST) under the Paris Agreement, National GHG inventories and biennial reports, and Voluntary corporate disclosures and sustainability standards. However, challenges relating to data quality, greenwashing, and equitable implementation, continue to require focused attention.

Conclusion

The science behind global warming is grounded in physics. Human-enhanced greenhouse gas emissions are unequivocally altering Earth’s climate. Understanding the principles embodied by the science is vital for climate policy and innovation.

Energy systems are at the heart of the climate change challenge and solution. A rapid and just transition to low-carbon energy is imperative to limit global warming and secure a sustainable future. Industrialisation has historically driven emissions through fossil fuel-based energy use. Addressing industrial emissions is vital for climate goals and requires systemic shifts in energy, technology, and policy.

The carbon budget is a finite resource and a critical guide for climate policy. Energy systems are central to both the problem and the solution. Timely, equitable and at scale energy transitions are essential to stay within safe climate limits and avoid the most catastrophic consequences of global warming. Sustainable industrial development is both a necessity and an opportunity in the fight against climate change.

Long-term climate goals and net-zero commitments are pivotal to avoiding catastrophic climate change. Their effectiveness hinges on credible plans, transparent monitoring, and equitable implementation. Net-zero is not just a destination; it is a framework for immediate and sustained climate action.


03

CHAPTER 03

GLOBAL ENERGY POLICIES AND THE PARIS AGREEMENT

Global energy policy is undergoing a major transformation to address climate change, with the Paris Agreement as a central driver. Adopted in 2015 by 196 parties at 2015 Paris Climate Conference (COP21), the agreement aims to limit global warming to well below 2°C, preferably 1.5°C, above pre-industrial levels. Meeting these targets requires a shift toward low-carbon energy systems.

Since then, countries have embedded climate goals into their energy strategies, setting renewable targets and net-zero pledges. However, the Paris Agreement's mechanisms – Nationally Determined Contributions (NDCs) and the five-year Global Stocktake (GST), highlight a persistent gap between current efforts and what's needed to stay within the temperature thresholds.

Analysis of initial NDC pointed to a potential 3°C rise by 2100, prompting calls for greater ambition. In response, global collaboration has intensified through consensus-building, stronger policy tools like carbon pricing and emissions trading, and initiatives accelerating clean energy transitions. Recent milestones, including the "UAE Consensus", reached at 28th United Nations Climate Change Conference (COP28) in 2023, have further influenced global energy governance and policy direction. ▸

Key Points

Signed in 2015, the Paris Agreement established a universal, legally binding framework to limit global warming to well below 2°C, with efforts to cap it at 1.5°C. All signatories must submit and update NDCs, aligning national policies with these goals. Early NDCs projected around 3°C of warming by 2100, exposing a major ambition gap. In response, the GST was created to regularly assess progress and drive stronger action. The first GST at COP28 confirmed significant shortfalls, catalysing global momentum. The resulting "UAE Consensus" included a call to triple renewable energy capacity to 11,000 GW by 2030 – highlighting renewables' central role in narrowing the gap. Since then, major economies like the European Union (EU), United States, China, and Japan have strengthened climate policies, committing to net-zero targets and scaling up renewable energy and efficiency measures. However, progress remains uneven. Developed countries lead the transition, while many developing and fossil-fuel-reliant nations are in early stages of reform. Bridging this divide requires greater international cooperation, with climate finance and technology transfer critical enablers. In 2022, the EU and member states provided €28.5 billion to developing countries, with ~32% directed to Africa and 27% to Asia. Strengthening global partnerships, sharing best practices, and advancing inclusive policy frameworks will be vital to fully realising the Paris Agreement's objectives.

Nationally Determined Contributions (NDCs): How Effective Are They?

The Paris Agreement introduced a landmark framework for global climate action, built around NDCs—national pledges to cut emissions and boost resilience. This bottom-up approach allows countries to set their own targets in pursuit of the collective goal to limit warming to well below 2°C, with an ambition of 1.5°C.

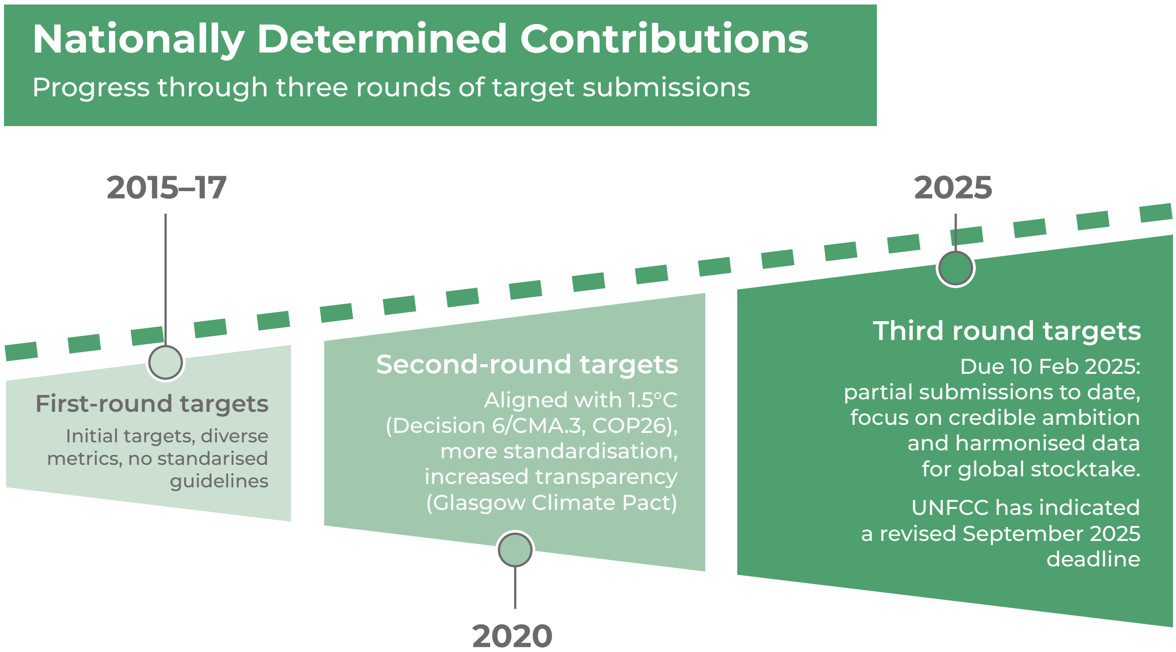
NDCs are the primary mechanism through which the Paris Agreement translates global climate ambition into national action. NDCs are the cornerstone of the Paris Agreement, allowing countries to articulate their climate goals and strategies.

Originally introduced ahead of COP21, Intended Nationally Determined Contributions (INDCs) formed the basis of countries' early climate pledges. Upon ratification of the Paris Agreement, these INDCs transitioned into formal NDCs. To date, the NDC process has progressed through three rounds of target submissions, each expected to reflect increased ambition over time. Figure 1 illustrates the evolution of these NDC rounds and various key attributes.

Early assessments revealed that the initial NDCs submitted in 2015 were far from adequate. A United Nations Framework Convention on Climate Change (UNFCCC) synthesis report found that projected 2030 emissions would place the world on a >3°C warming trajectory, far exceeding the Paris targets. Scientific studies, including the IPCC's Special Report on 1.5°C and the annual Emissions Gap Reports, echoed these concerns, stressing that the pledged efforts fell short of what's needed for either 2°C or 1.5°C scenarios.

The widespread recognition of the ambition gap led to calls for stronger commitments. The Paris Agreement built in a "ratchet mechanism" requiring countries to regularly revise and enhance their NDCs, aiming to close the gap and steer global efforts toward meeting long-term climate goals.

By 2020–2021, countries were expected to submit updated NDCs. Despite COVID-19 delays, many did. Notably, the United States rejoined the Paris Agreement with a 50–52% reduction target by 2030, while the EU raised its goal to at least 55%. These steps marked progress but remained insufficient. Analyses around the 2021 United Nations Climate Change Conference (COP26), including a 2021 UNFCCC report and Climate Action Tracker (CAT), projected warming of 2.4°C even if all pledges were met. This shortfall persisted in later assessments. The UNFCCC's 2023 synthesis report found improved ambition, including widespread net-zero targets, yet warming projections stayed around 2.5°C. CAT's 2023 update estimated 2.7°C under current policies, and 2.4–2.5°C even if all pledges were fully implemented. UNEP's 2023 Emissions Gap Report reiterated that only rapid, systemic change can keep 1.5°C within reach.



Source: Al-Attiyah Foundation

Figure 1: Progression of NDC Target Rounds, Highlighting the Envisaged Increase in Ambition and the Collective Scale of Contributions Over Time.

A major barrier is finance. Many developing countries' pledges are conditional on support—especially the unfulfilled $100 billion/year climate finance goal that is now being replaced by the recent $300 billion/year pledge at COP30. Technology and sectoral transitions remain uneven. The IEA's 2023 Net Zero roadmap warned that emissions must peak immediately and fall 45% by 2030 for even a 50% chance of limiting warming to 1.5°C—far beyond what current NDCs deliver. The first GST, concluded at COP28, confirmed the insufficiency of current efforts and called for more ambitious action. Key outcomes included a call to triple renewable energy capacity by 2030, double the rate of energy efficiency, and transition away from unabated fossil fuels—strong signals yet to be fully translated into national policy. COP28 also reinforced the urgency of enhanced NDCs by 2025, emphasising peak emissions by 2025 and halving them by 2030. The UAE Presidency prioritised climate finance reform and clean tech investment, especially for the Global South. The GST has increased pressure on countries to deliver bolder NDCs in the 2025 cycle. The credibility of the Paris Agreement now hinges on how effectively nations rise to this challenge in the decisive years ahead.

The bottom-up structure of the NDC encouraged nearly universal engagement and national ownership of climate plans. Unlike the Kyoto Protocol's top-down targets, the Paris model lacks strict enforcement, relying instead on transparency, peer pressure, and regular stocktakes to drive progress. This "pledge and review" system has prompted incremental increases in ambition—especially visible in the 2020–2021 NDC updates—but progress remains too slow to meet climate goals. Scholars and analysts have praised the inclusive nature of NDCs but caution that, without stronger accountability or supplemental measures, the aggregated pledges will fall short of what is needed for climate stabilisation.

The credibility of the Paris Agreement now hinges on how effectively nations rise to the 2025 challenge.

COP28 and the UAE Consensus: A Turning Point

COP28 in Dubai was widely seen as a pivotal moment where the global community had to respond to the GST's findings. In the final hours of the conference, parties reached a negotiated outcome termed "The UAE Consensus," which serves as the formal response to the GST. The UAE Consensus (named after the host country's presidency) is significant both substantively and symbolically: it is the first comprehensive climate decision informed by a GST, effectively a blueprint for closing the gaps identified.

Mitigation and energy transition: The UAE Consensus represents a pivotal moment in global climate diplomacy. For the first time, a COP decision invites all countries to transition away from unabated fossil fuels, signalling a shift toward net-zero emissions by mid-century. Although debates over terms like "phase out" persisted, the outcome marked historic progress.

Tripling renewable energy capacity and doubling energy efficiency: The COP28 agreement also introduced two global targets – tripling renewable energy capacity and doubling energy efficiency improvements by 2030 (relative to 2020). These goals—about 11,000 GW of renewables and ~4% annual efficiency gains—align with IEA benchmarks for keeping 1.5°C within reach. This quantitative addition to the Paris framework supports the implementation of NDCs by offering a shared roadmap for global progress.

Enhanced NDCs and the 2025 cycle: COP28 strongly encouraged countries to submit ambitious, economy-wide emission reduction targets in their next NDCs—due in 2025, often termed "NDCs 3.0." The guidelines agreed for NDCs 3.0 reflect a growing consensus on what constitutes a credible NDC, shifting the norm away from partial or conditional targets and increasing peer pressure on lagging countries. With time running out to align global emissions with the 1.5°C pathway, the UN has warned this may be the last viable opportunity to course correct.

Finance and support: The success of NDCs depends on financial and technical support. COP28 made progress by operationalising the Loss and Damage Fund to assist vulnerable nations—an important trust-building step. In addition, over $85 billion was pledged across climate finance initiatives, including efforts to reform development banks and mobilise clean investment. While still far below what's needed, these actions underscore the central role of finance in delivering climate goals.

The UAE Consensus serves as a strategic inflection point. While it doesn't directly reduce emissions, it establishes clear global expectations: transition from fossil fuels, triple renewables capacity, double energy efficiency, and prepare more ambitious NDCs by 2025. These elements now set the benchmark against which future commitments will be judged.

COP28 urged nations to deliver ambitious, economy-wide targets in their 2025 NDCs—often called 'NDCs 3.0'—a last chance to course-correct toward 1.5°C.

A Normative Appraisal of NDC Effectiveness

After eight years, the performance of NDCs under the Paris Agreement highlights both achievements and shortcomings of a pledge-based system. On the positive side, NDCs have enabled near-universal climate participation and iterative ambition. Initial pledges pointing to ~3°C of warming have shifted closer to 2°C, driven by net-zero targets and the Paris Agreement's "ratchet mechanism." This process has fostered national climate planning, integrated goals into domestic policies, and established a transparency system that enhances accountability—boosting the legitimacy of the Paris framework. Yet, measured against climate science, NDCs remain insufficient. Current pledges project a 2.5–2.9°C trajectory, well above the 1.5°C goal, and global emissions are not falling fast enough. Key shortcomings include weak ambition, poor implementation, and inequities—especially for countries with conditional or unmet pledges. In sum, the NDC process has narrowed but not closed the emissions gap. Strengthening it—through deeper ambition, improved implementation, and equitable support—is essential.

Key Policy Instruments: Carbon Pricing, Emissions Trading, and Regulatory Frameworks

Global efforts to meet Paris Agreement targets have driven the adoption of diverse policy instruments to cut greenhouse gas emissions. Effective climate action relies on a mix of well-aligned technology innovation, carbon pricing, regulatory frameworks, cooperative approaches and financial tools—supported by strong governance and adequate funding. This section focuses on three key categories: carbon pricing and market mechanisms, regulatory policies, and financial instruments. Recent developments, including outcomes from COP28, have advanced global energy policy across all three areas. Increasingly, the design and implementation of these tools are shaped by priorities of economic efficiency, policy diffusion, and environmental justice, reinforcing the growing consensus that successful climate mitigation must be both cost-effective and equitable.

Carbon Pricing and Market Mechanisms

Carbon pricing has become a cornerstone of global climate policy for its efficiency in reducing emissions by internalising the social cost of carbon. Whether implemented as a carbon tax or an emissions trading system (ETS), it incentivises emitters to adopt lower-carbon alternatives, often at a lower cost than traditional regulations. Since 2020, adoption has grown rapidly, with over 25% of global emissions now covered by some form of carbon pricing, including in emerging economies like China, Brazil, Chile, and South Africa.

ETS and Global Diffusion: Cap-and-trade systems, like the EU ETS set an emissions cap and allow trading of allowances. The EU has reformed its ETS to align with its 55% emissions reduction target by 2030, expanding coverage to new sectors and adding tools like the Market Stability Reserve and Carbon Border Adjustment Mechanism (CBAM). In 2023, it generated €43.6 billion for climate programmes. Other ETSs include those in China, California, Québec, the United Kingdom (UK), and New Zealand, all tailored to local needs but contributing to global policy diffusion.

Carbon Taxes and Hybrid Models: Carbon taxes offer an alternative by directly pricing emissions. Canada's national carbon price, rising to C$170/ton by 2030, rebates most revenue to households, making it progressive. Sweden, Chile, and South Africa have also implemented carbon taxes, and some systems blend tax and trading features. If well-designed, both approaches can drive similar outcomes, with hybrid models offering added flexibility.

Effectiveness and Political Realities: Despite growing coverage, most carbon prices remain too low to meet Paris Agreement goals. Fewer than 1% of emissions are priced at levels (~$50–100/ton) needed to stay below 2°C. Political resistance, economic concerns, and social backlash to ensure climate justice —such as France's "gilets jaunes" protests—have hindered ambition. Still, international norms and peer influence are pushing more countries to adopt or strengthen carbon pricing.

Carbon pricing is a powerful tool for emissions reduction, but its success depends on political will, involvement of communities and affected stakeholders, equity considerations, and integration with broader climate policy. When paired with social protections and other climate measures, it can deliver both environmental and economic benefits.

Regulatory Policies and Financial Instruments

Command-and-Control Regulations: Alongside carbon pricing, governments increasingly rely on direct regulations—such as emissions standards, technology mandates, and clean energy targets—to drive decarbonisation, particularly in sectors where market signals alone may be too slow. Since 2023, over thirty-five countries (covering one-fifth of energy-sector CO_2 emissions) have adopted new or stricter rules, especially in transport and power. The EU plans to phase out combustion-engine car sales by 2035, while the United States, China, and others have tightened vehicle CO_2 and fuel economy standards. New power plant CO_2 limits, renewable portfolio standards, and efficiency codes are also being implemented, alongside regulations like the EU's F-gas ban and biofuel mandates in countries such as Ukraine. Green public procurements is also being more and more developed. These policies deliver clear outcomes and co-benefits (e.g., cleaner air), but may be less cost-efficient than market-based tools and are vulnerable to poor enforcement or political reversal—evident when some countries softened green rules after the 2021–2022 energy price crisis. But when price certainty is needed and /or when revenues are needed for redistribution or green spending, regulations are more suitable.

Financial Instruments and Incentives: Since 2020, public spending on clean energy has surged, with governments pledging over $2 trillion globally—three times the green stimulus post-2008. Key examples include the United States Inflation Reduction Act ($370+ billion), the EU's Green Deal and recovery funds, and China's renewable and EV investments. Renewable energy auctions have driven prices to record lows—e.g., solar bids in India at $0.03/kWh—making clean power more competitive than fossil fuels in many regions. Additional tools include tax credits, subsidies for EVs and energy efficiency, and R&D support for technologies like batteries and carbon capture.

Green Finance and Markets: Green finance is expanding rapidly, with $575 billion in green bonds issued in 2023. Instruments like sustainability-linked loans and climate funds are mobilising private capital, while development banks offer guarantees and results-based financing to de-risk low-carbon projects. Global efforts are also focusing on reforming financial systems to better channel climate finance to developing countries, recognising the multi-trillion-dollar scale needed to meet climate goals. New instruments such as the integrated green bond and carbon market have been tested.

Integrated Approaches and Justice: Technology innovation, regulatory and financial tools increasingly complement carbon pricing in comprehensive climate strategies. Carbon prices provide broad incentives, while technology innovations and regulations enable specific actions (e.g., EV deployment), and financial measures address cost barriers. These policies are also being designed with equity in mind—supporting workers and communities in transition, embedding social benefits in clean energy auctions, and directing finance to vulnerable regions.

The Effectiveness of Energy Transition Policies Across Different Economies

The Paris Agreement established a universal but differentiated framework for countries to limit global warming to well below 2°C and pursue 1.5°C. Meeting these goals requires a rapid energy transition worldwide, yet the effectiveness of policies has varied widely across high-income countries, economies in transition, and developing nations. This section provides an integrated analysis of energy transition policies in selected economies – examining progress, limitations, and equity considerations – and evaluates their alignment with the Paris Agreement. Key indicators such as growth in renewable energy capacity, implementation of policy instruments, and outcomes in emissions are assessed in the context of the first GST, which highlights both advances and gaps in global climate action. The discussion also addresses the principles of equity and just transition, including climate finance, technology transfer, and support frameworks that aim to ensure all countries and communities can participate in and benefit from the clean energy transition.

Advancing Global and Equitable Renewable Energy Transition

The global shift to sustainable energy is accelerating, but progress remains uneven across countries and regions. While some nations have advanced rapidly in clean energy adoption, others face persistent structural and financial obstacles. These disparities reflect a deeper equity challenge—one that threatens the collective success of the Paris Agreement. With the energy sector responsible for over 70% of global emissions, decarbonisation is essential to meeting climate goals. Achieving the Paris temperature targets requires a swift, far-reaching transformation of energy systems. The COP28 call to triple global renewable capacity by 2030 highlights the urgency. However, this leap must be not only accelerated—but also inclusive. Ensuring that all regions can participate equitably is critical to a just and effective global transition.

> Carbon pricing is a powerful tool for emissions reduction, but its success depends on political will, involvement of stakeholders, equity considerations, and integration with broader climate policy.

Leaders and Laggards: Disparities in Progress

Leaders by Total Installed Renewable Capacity (2024) are China, US, Brazil, India, Germany. Leaders by Share of Electricity from Renewables (2024) are Iceland, Norway, Paraguay, Uruguay, Denmark, and New Zealand. Fastest-Growing Renewable Energy Markets are Vietnam, Chile, Morocco, Kenya, South Africa, and Indonesia.

Thanks to forward-looking policies and consistent investments over the past two decades, countries like Germany and Denmark now derive over 40% of their electricity from renewable sources. The European Green Deal further institutionalises this momentum by targeting climate neutrality by 2050 and channelling substantial funds into clean energy and innovation.

Importantly, Europe is also extending support to other regions. In 2022, the EU, its member states, and the European Investment Bank collectively disbursed €28.5 billion in climate finance to developing nations, with Africa and Asia receiving nearly 60% of this support. These contributions are vital for countries that lack the financial capacity to invest in clean technologies on a scale.

In contrast, many developing and fossil fuel–dependent economies remain at the initial stages of their energy transitions. In regions of the Middle East, Africa, and Asia, renewable sources still constitute a minor share of energy supply. Structural barriers—ranging from limited capital and weak regulatory frameworks to heavy reliance on fossil fuels—continue to hamper progress. Even where governments have announced renewable targets, such as installing 4 GW of clean capacity by 2030, the scale often falls short of what is required to drive deep decarbonisation. Inadequate grid infrastructure and surging energy demand further complicate the shift, making external support and technology transfer critical.

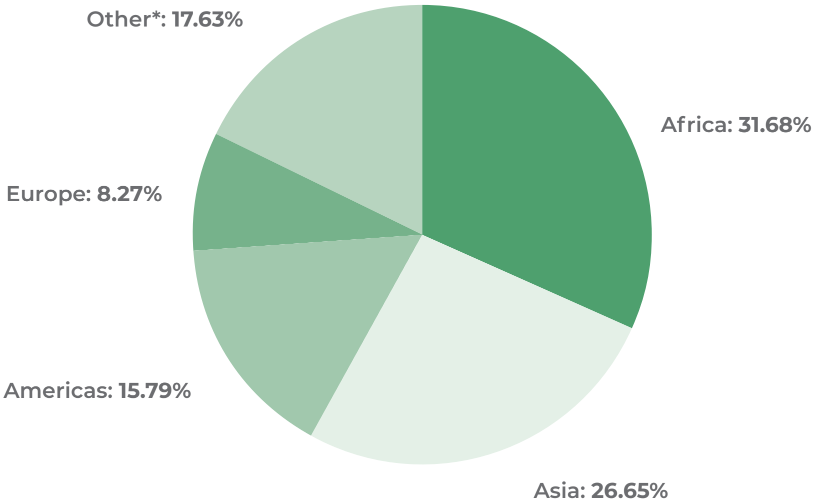


Figure 2. The Geographical Distribution of EU Climate Finance (Source: European Commission)

Figure 2 underscores the EU's global commitment to advancing renewable energy and climate adaptation. In 2022, the EU, its member states, and the European Investment Bank jointly contributed €28.5 billion in public climate finance to developing economies. Africa received the largest share (31.7%), followed by Asia (26.7%), the Americas (15.8%), Europe (8.3%), and 17.6% classified as 'Other'. The allocation reflects the EU's active role in promoting clean energy and climate resilience worldwide, with a clear emphasis on Africa and Asia—regions most vulnerable to climate impacts.

Closing the Gap: Finance, Technology, and Capacity

Developed nations are expected to lead not only in ambition but in support. This means significantly scaling up international climate finance to meet and exceed the $300 billion annual target by 2035 set under the UNFCCC. These funds can be used to build renewable infrastructure, enhance electricity access, and improve climate resilience in underserved regions. At the 2024 United Nations Climate Change Conference (COP29) in Baku, the final deal on climate finance, the central focus at the event, encouraged the developed countries to provide $300bn in funding per year by 2035 to support developing countries dealing with the impact of climate change.

Technology transfer and capacity-building are equally important. Sharing best practices—such as renewable auctions or feed-in tariffs—and investing in workforce development can empower countries to adopt cleaner systems quickly and effectively. Digital technologies such as 5G, AI, IoT and DLT as well as innovations like floating wind farms, next-generation solar cells, and green hydrogen also need to be made accessible to developing economies to support leapfrogging into intelligent power over outdated energy technologies.

Encouragingly, initiatives like the Just Energy Transition Partnerships (JETPs) are beginning to address these equity gaps. Countries such as South Africa, Indonesia, and Vietnam are receiving international support to transition away from coal, while institutions like the International Renewable Energy Agency (IRENA) and the IEA emphasise the importance of inclusive, people-centred approaches that pair emissions cuts with energy access and economic development.

Accelerating Deployment: The Road Ahead

To meet the 2030 targets, global renewable energy capacity must grow by around 15% annually, nearly double the current pace. Achieving this requires a multifaceted strategy:

- Infrastructure Investment: Upgrading transmission grids and deploying energy storage are essential for integrating intermittent sources like wind and solar.
- Technological Innovation: Continued R&D is vital to advance clean energy technologies, improve efficiency, and reduce costs. Leapfrog to intelligent power that integrates data analytics, AI, and real-time decision-making to optimise power flows, ensure resilience, and respond dynamically to changing conditions. Its core features include AI-based decision-making, predictive maintenance, autonomous control (e.g., load shedding, storage dispatch), Grid-edge intelligence (e.g., smart inverters, EV-to-grid).
- Innovative financial instruments such as an integrated green bond and carbon market
- Policy Support: Effective policy instruments—including auctions, subsidies, tax incentives, and carbon pricing—must be scaled and harmonised to drive private investment.
- International Coordination: Sustained diplomatic engagement, trust-building, and fulfilment of financial commitments are critical to ensure all countries can contribute to and benefit from the energy transition.

While the challenges are considerable, so too are the opportunities. Clean energy is becoming more affordable and scalable, and strong policy action can close the gap between current trends and the pathways needed to limit warming.

High Income Economies: Progress and Challenges in the Energy Transition

A pioneer of the Energiewende, Germany aims for net-zero emissions by 2045, with 80% renewable electricity by 2030 and 100% by 2035. In 2023, it completed its nuclear phase-out, accelerated coal retirements, and expanded renewables—targeting 110 GW onshore wind, 30 GW offshore wind, and 200 GW solar by 2030. Renewables surpassed 50% of net electricity in 2023, though onshore wind growth lags, and grid/storage constraints remain. The 2022 energy crisis briefly increased coal and gas use, prompting a renewed focus on energy efficiency. Sustained policy, infrastructure upgrades, and public support are essential to meet future goals.

Italy is progressing toward carbon neutrality by 2050, aiming for 30% renewables in total energy and 55% in electricity by 2030. Currently, renewables supply ~20% of primary energy and 40–45% of electricity, with solar PV, wind, hydro, and geothermal playing key roles. Solar surged to 20 GW and is expanding again with EU support. The 2022 gas crisis accelerated diversification via liquefied natural gas (LNG) , new pipelines, and efficiency efforts. Incentives like the Super Bonus target building emissions, while auctions support renewables. Yet, challenges include permitting delays, southern grid bottlenecks, and high electricity prices. Continued reforms are needed to reduce gas reliance.

The United States, the world's second-largest emitter, committed to a 50–52% GHG cut by 2030 after rejoining the Paris Agreement in 2021. The Inflation Reduction Act (IRA) and Infrastructure Investment and Jobs Act direct over $369 billion to clean energy, aiming to reduce emissions, attract $350 billion in private investment, and create ~300,000 jobs. By 2023, clean energy investment surged, energy intensity improved by ~4%, and emissions fell despite ~2.5% GDP growth. The United States targets 100% carbon-free electricity by 2035, requiring 2,000 GW of new capacity. Yet, grid congestion, permitting delays, and political threats to climate policy persist. The current United States Administration under President Trump has again pulled out from the Paris Agreement. Overall, Climate Action Tracker rates United States policy as insufficient for 1.5°C alignment, underscoring the need for consistent implementation and grid reform.

Canada seeks 40–45% emissions cuts by 2030 and net-zero by 2050, balancing ambition with its fossil fuel-based economy. It leads in carbon pricing, with a national system set to reach C$170/ton by 2030. The power sector is already 83% non-emitting, with a 100% net-zero grid goal by 2035. Just transition measures and clean energy incentives support this effort. Challenges include the oil and gas sector (~25% of emissions), rising oil sands and methane emissions, and fragmented provincial cooperation. Though Canada has strong policies, implementation gaps and continued fossil fuel expansion threaten progress. Climate Action Tracker rates its efforts as needing improvement.

Historically reliant on coal, Australia has shifted direction with the Climate Change Act 2022, targeting 43% emissions cut by 2030 and net zero by 2050. It aims for 82% renewable electricity by 2030, up from ~30% in 2022. The country leads globally in per-capita rooftop solar, with wind also expanding. The IEA projects a ~40 GW increase in renewables by 2027. Key initiatives include Renewable Energy Zones, a National Net Zero Authority, and green hydrogen and critical minerals strategies. Challenges include grid stress, coal dependency, climate vulnerability, and political instability. Large-scale storage (e.g., Snowy 2.0) and public support are helping drive change, but infrastructure and integration remain key hurdles.

Economies in Transition: Shifting from Fossil Legacies

Economies in transition, primarily from the former Soviet Union, face distinct energy transition challenges. Their inherited fossil fuel-based infrastructure contrasts with rising climate ambitions and renewable potential. This section explores the energy transition trajectories of Azerbaijan, Georgia, and Ukraine, shaped by policy reforms and recent geopolitical dynamics.

A major oil and gas exporter, Azerbaijan remains heavily reliant on fossil fuels—particularly natural gas—for electricity and revenue. Renewables made up just 5% of power in 2020, down from ~18% in 2010 due to declining hydro output. In 2021, a renewable energy law set a target of 30% of installed capacity from renewables by 2030, requiring 1–1.5 GW of new wind and solar. The government partnered with firms in Saudi Arabia and UAE to install 700 MW of new capacity, aiming to free gas for export to Europe amid rising post-2022 demand. EU support has bolstered renewables planning and grid integration. However, Azerbaijan's overall climate policy remains weak. Emissions are projected to rise, and its 2050 goal of a 40% cut from 1990 levels is widely seen as inadequate. Structural barriers include dominant state-owned firms, lack of carbon pricing, and a continued focus on gas exports. The next few years will test whether Azerbaijan can transition meaningfully from hydrocarbons.

Georgia has aligned its energy transition with EU climate standards, anchored by a low-carbon electricity mix dominated by hydropower (70–80%). This reliance, however, makes the country vulnerable to droughts. To diversify, Georgia launched its first wind farm in 2017, initiated further wind projects in Kartli, and promoted rooftop solar via net metering. Its 2019 renewable energy law introduced feed-in premiums and auctions, and the draft National Energy and Climate Plan targets 27.4% renewables in total final energy use by 2030. The updated NDC commits to a 35% emissions cut from 1990 levels by 2030 and carbon neutrality by 2050, supported by energy efficiency measures and gas-to-electricity switching. Seasonal imbalances—requiring winter imports from Azerbaijan—highlight the need for more diversified domestic capacity. International support has strengthened Georgia's policy landscape, but capacity growth remains slow, and energy intensity is high. The coming decade will be crucial for scaling investment and implementation.

Despite war, Ukraine remains committed to a cleaner, more resilient energy system. Pre-2022, the country aimed to shift from its coal- and gas-heavy mix (with nuclear supplying ~50% of electricity) toward renewables, which reached ~12–13% of generation by 2020. The 2021 NDC targeted a 65% emissions cut by 2030 and 25% renewables by 2035. Russia's invasion severely damaged infrastructure, prompting a pivot to decentralised, resilient solutions, including solar-plus-battery microgrids and greater ENTSO-E grid integration. In 2023, Ukraine set a new goal: 50/50 power generation split between renewables and nuclear by 2035. Although conflict has delayed progress, reconstruction offers opportunities to expand clean energy, smart grids, and technologies like modular nuclear and green hydrogen. International donors are backing efforts to replace centralised heating with efficient biomass systems and fund sustainable rebuilding. Ukraine's energy transition remains aligned with Paris goals, with future success hinging on peace, investment, and infrastructure resilience.

Developing Economies: Diverse Pathways and Imperatives

Developing countries face the dual challenge of expanding energy access and supporting economic growth while aligning with global climate goals. Their transition paths vary—from high-income fossil fuel exporters to low-income nations tackling energy poverty. The following cases illustrate the diversity of progress and obstacles across the Global South.

With a population of 270 million, Indonesia remains coal-dependent—coal supplied ~60% of electricity in 2020, while renewables (mainly geothermal and hydro) contributed less than 15%. In 2022, the country joined the $20 billion Just Energy Transition Partnership (JETP) with the United States, Japan, and others to phase out coal and boost renewables. The goal: cap power-sector CO_2 emissions at 290 Mt by 2030 and raise renewables' share to 34–44%. Supporting policies include feed-in tariffs, auctions, a coal moratorium post-2025, and early retirement of 9.5 GW of coal. Challenges include PLN's reluctance to integrate variable renewables, regulatory inconsistencies, and distorting fossil fuel subsidies. Yet momentum is growing around green industrialisation, especially EV and battery manufacturing, leveraging Indonesia's nickel reserves. The JETP emphasises equity through worker protections and economic diversification.

South Africa depends on coal for 70–80% of its electricity and employment, making decarbonisation complex. It launched the first JETP at COP26 in 2021, securing $8.5 billion to retire coal, expand renewables, and support workers. Its 2019 Integrated Resource Plan calls for 10 GW of coal retirements and 18 GW of renewables by 2030, aiming for a 25–30% renewable share. The Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) has added ~6 GW, but progress has slowed due to Eskom's (South Africa's state-owned electricity provider) financial woes and permitting delays. In response, South Africa is fast-tracking battery storage and emergency procurement to address load shedding. Public demand for reliable, affordable energy highlights the need to prove renewables' reliability. Equity remains central, with rooftop solar for underserved areas and tariffs to protect low-income households. The JETP is a comprehensive approach integrating climate, social, and energy priorities.

Brazil leads among major economies in clean energy, with 45% of primary energy and 93% of electricity from renewables in 2023—mainly hydropower, biofuels, wind, and solar. In 2023 alone, wind and solar added ~8.4 GW, bringing renewables to over 83% of installed power capacity. Under President Lula, Brazil passed a National Energy Transition Law and established an Energy Transition Fund to support green technology and exports. Plans include over 50 GW of new wind and solar by 2030, investments in offshore wind, and grid modernisation. Key challenges remain emissions from fossil fuel extraction, exports, and deforestation. The government is responding with transport electrification, Renova Bio biofuel incentives, and green hydrogen initiatives. If fully implemented, Brazil's transition policies could exceed Paris-aligned targets, demonstrating a strategic, policy-driven model for low-carbon development.

Colombia is reorienting its energy policy to reduce fossil fuel dependence, building on a largely clean electricity mix—over 70% from hydropower—though vulnerable to drought. Since 2019, it has allocated 2.2 GW of solar and wind through auctions, targeting 4 GW by 2024–2025. Under President Gustavo Petro, the government declared a "fair energy transition," paused new oil and gas licenses, and launched a $40 billion plan focused on clean energy, grids, and a Just Transition Fund. Despite this, fossil fuels still

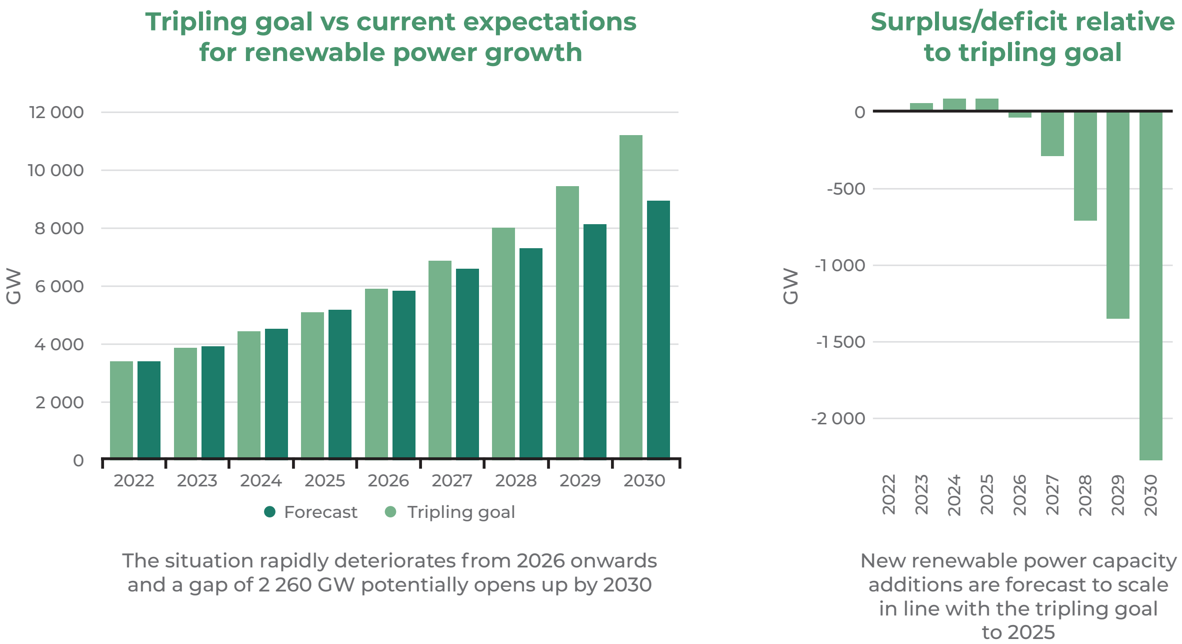


Figure 3: Current Expectations of Global Cumulative Renewable Power Capacity to 2030 Compared to the Tripling Goal, 2022-2030 (Source: IRENA 2024)

provide ~8% of national revenue, and the shift faces local opposition—particularly to wind projects in La Guajira—and bureaucratic delays. Colombia's updated NDC targets 51% emissions cut below business-as-usual by 2030, with ongoing efforts in green hydrogen and renewables. Its experience highlights the importance of social justice, community engagement, and regulatory reform for an inclusive transition.

Technology and Innovation in Future Energy Transitions

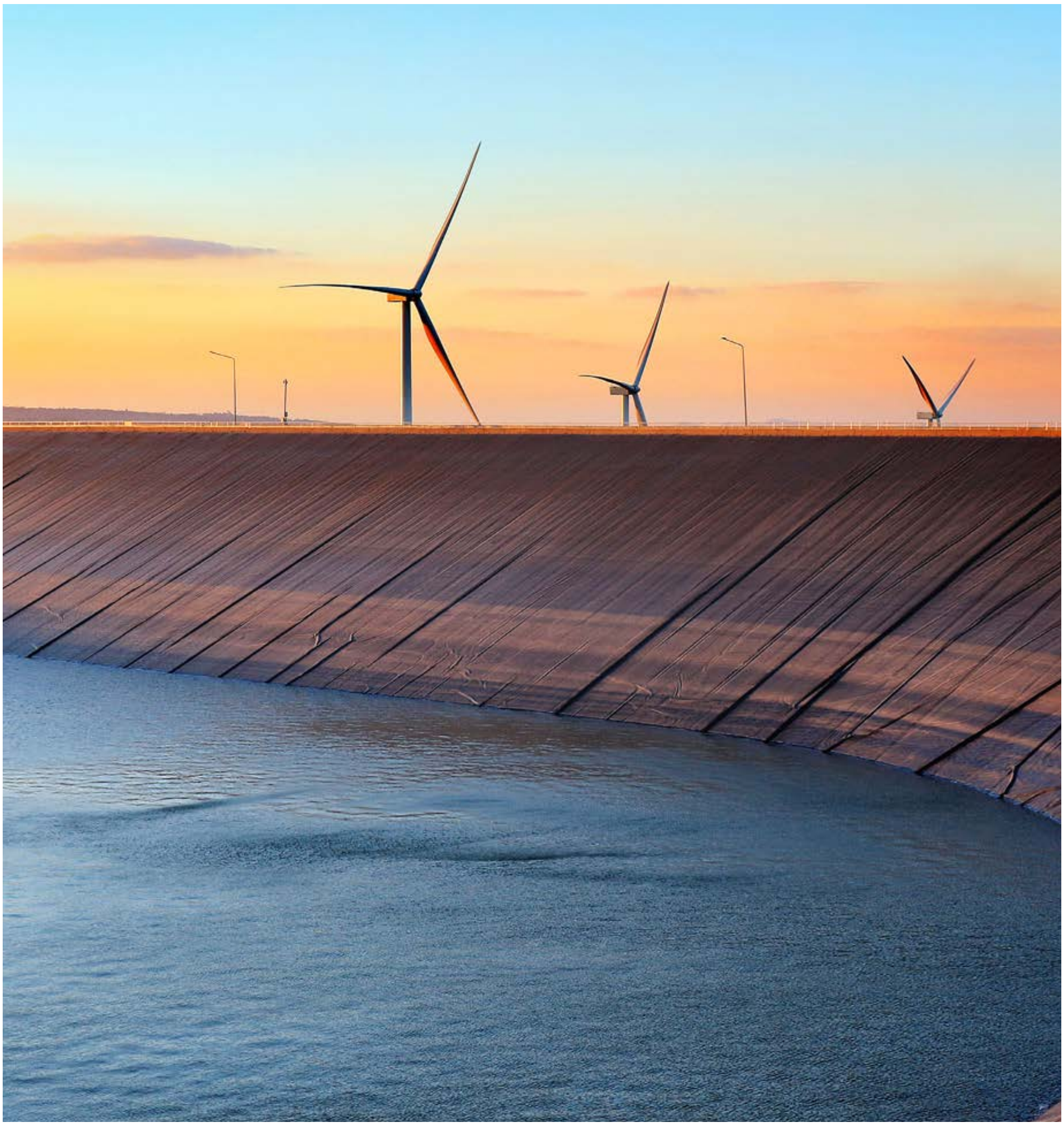
Innovation in clean energy—solar, wind, storage, and green hydrogen—is essential to close the gap to the 1.5°C target. Indeed, the energy transition will be a twin green and digital transition. As shown in Figure 3 (IRENA, 2024), current renewable capacity projections fall short of the 2030 tripling goal, highlighting the urgent need for accelerated technology deployment, supportive policies, and global diffusion.

Technological innovation is key to meeting climate goals. Cost drops of up to 85% in solar, wind, and batteries have made renewables and EVs mainstream. Now, innovation must be scaled up in the power and harder-to-abate sectors—like heavy industry and aviation—through significant decrease in the cost of green hydrogen and carbon capture.

The IEA forecasts rapid progress by 2030: EVs could grow tenfold, renewables may supply nearly half of global power, and fossil fuel demand may peak. Policies like the IRA in the United States, EU Green Deal, and Mission Innovation are advancing next-gen technologies. Ensuring equitable access through technology transfer and capacity-building is vital for a just, Paris-aligned transition.

Conclusion

The Paris Agreement has fundamentally reshaped global energy governance, transforming climate action into a collective endeavour of ambition and implementation. Yet, its success now hinges on turning commitments into concrete actions and impact. COP28 and the first GST mark a critical juncture, with the UAE Consensus—calling for a tripling of renewable energy capacity by 2030—underscoring the urgency for bold policy, innovation, and cooperation. A sustainable, low-carbon future depends on five key strategies: (1) stronger national frameworks, (2) rapid scale-up of clean energy and intelligent power, (3) investment in innovation prioritising transformative innovation over the incremental ones, (4) deeper global cooperation across nations as well as radical collaboration within nations aligning NDCs, the national energy strategy and local strategy plan with the countries Long Term Low Emission Development Strategies, and (5) a just, inclusive transition. Most of the tools and frameworks are in place—what is needed now is sustained political will and implementation at scale. By aligning ambition with impactful action, and embedding fairness and innovation at the core, the next decade will determine whether the international community can stay on course for the 1.5°C goal and meet the defining challenge of our time.




04

CHAPTER 04

THE IMPACT OF ENERGY SUBSIDIES – ARE THEY HELPING OR HURTING?

This chapter offers a comprehensive analysis of energy subsidies, with a particular emphasis on fossil fuel subsidies and their wide-ranging implications for economic efficiency, environmental sustainability, and social equity. Broadly defined, energy subsidies are non-reciprocal financial transfers or interventions—such as tax exemptions, direct fiscal support, and price controls—that reduce the cost of producing or consuming energy. Such measures may be either explicit, like budgetary outlays, and implicit forms, such as under-pricing by state-owned enterprises. Governments often justify such subsidies on the grounds of poverty alleviation, energy affordability, industrial development, and political stability, particularly in low- and middle-income countries where access to modern energy services remains limited.

Despite their perceived short-term benefits, fossil fuel subsidies have come under increasing global scrutiny. They are widely criticised for distorting market signals, encouraging overconsumption, discouraging energy efficiency, and undermining investment in renewable technologies. The International Monetary Fund (IMF) estimated that global fossil fuel subsidies reached $5.9 trillion in 2020 and rose to an estimated $7 trillion by 2022—equivalent to over 7% of global GDP. These subsidies are commonly divided into pre-tax subsidies (direct financial transfers or price controls) and post-tax subsidies (the failure to price externalities such as carbon emissions, local air pollution, and climate-related damages). When such externalities are not accounted for in pricing, the actual economic and environmental cost of subsidies becomes substantially greater.

The persistence of fossil fuel subsidies disproportionately benefits wealthier households that consume more energy, thereby exacerbating income inequality and creating significant fiscal burdens for governments. Critics argue that these subsidies are regressive, environmentally detrimental, and ultimately unsustainable. For example, subsidies for petrol or diesel often favour car-owning urban residents, bypassing the poorest segments of society who may lack access to modern fuels or rely on biomass.

This chapter further explores the political economy of subsidy reform, highlighting how entrenched interests, political sensitivities, and governance challenges make reform complex and contested. Through case studies of Indonesia and Ghana—two developing nations that have attempted subsidy reform—the analysis illustrates how policy success depends on enabling conditions such as public communication, institutional reforms, and compensatory mechanisms. In Indonesia, targeted cash transfers and civic engagement helped mitigate opposition, though inconsistencies in fuel pricing remain. Ghana's approach, which focused on liberalising prices and deregulating the energy sector, brought fiscal relief but introduced inflationary and equity concerns.

Finally, the chapter examines the implications of fossil fuel subsidies on clean energy investment. By distorting energy prices, these subsidies crowd out renewable alternatives and delay the transition to sustainable energy systems. Phasing out fossil fuel subsidies, therefore, is essential not only for improving fiscal health but also for aligning national policy with global climate goals, accelerating energy innovation, and ensuring a more equitable and sustainable development trajectory. ▸

The History and Impact of Fossil Fuel Subsidies

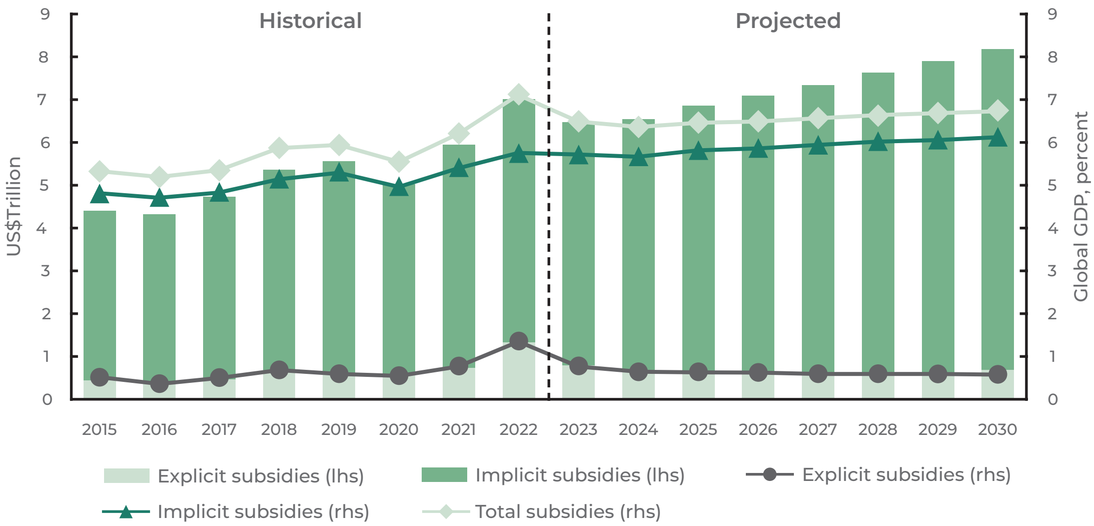
Historical Background

Fossil fuel subsidies have long-standing historical foundations rooted in national policies aimed at ensuring universal energy access, promoting industrial development, and shielding domestic producers from volatile global markets. Emerging in the early 20th century, these subsidies were initially introduced as instruments to stimulate industrialisation and enhance energy security. They played a particularly prominent role in the post-World War II era, when many countries, both developed and developing, adopted them as core components of their energy strategies. Over time, such measures became deeply entrenched in the policy frameworks of energy-rich states and resource-importing nations alike.

Every dollar spent keeping energy artificially cheap is a dollar diverted from health care, education, and infrastructure.

The IMF and the International Energy Agency (IEA) have repeatedly emphasised the enormous scale and persistence of fossil fuel subsidies. These are typically categorised into two types:

- **Pre-tax subsidies:** These reflect direct financial support that reduces energy costs for consumers and producers. For example: A government provides a fuel subsidy to state oil companies that allows them to sell gasoline to domestic consumers at a price lower than the international market price.
- **Post-tax subsidies:** These factor in the failure to price negative externalities such as greenhouse gas emissions, local air pollution, global warming, and traffic congestion. For example: If a country does not impose a carbon tax or does not fully tax gasoline consumption (e.g. no VAT, no excise duty), the gap between the efficient price (which includes environmental and health externalities) and the actual consumer price is considered a post-tax subsidy.



Source: IMF staff calculations. Note: 2019 and2022 onwards use projections of fuel use and fuel prices, respectively.

Figure 1: Global Fossil Fuel Subsidies (Pre-tax vs. Post-tax)

According to IMF estimates, globally, total fossil fuel subsidies amounted to $7 trillion in 2022, equivalent to nearly 7.1% of global GDP. Explicit subsidies or pre-tax subsidies (undercharging for supply costs) account for 18% of the total while post-tax subsidies or implicit subsidies (undercharging for environmental costs and forgone consumption taxes) account for 82%.

The above chart illustrates the sustained magnitude of fossil fuel subsidies, revealing that while pre-tax subsidies have fluctuated in response to oil prices and policy shifts, post-tax subsidies remain persistently high due to unpriced environmental and health externalities.

Types of Subsidies (Production vs. Consumption)

In addition to the definitions above, energy subsidies can be broadly categorised into production and consumption, each targeting different stages of the energy value chain and serving distinct policy objectives.

- **Production subsidies** are primarily directed at the upstream segment of fossil fuel markets. They include measures such as tax incentives, exploration and extraction grants, and preferential financing terms for fossil fuel companies. These subsidies aim to stimulate domestic energy production, reduce import dependency, and support energy security. Governments often justify such interventions as necessary to encourage investment in resource-intensive activities such as oil and gas drilling, coal mining, and infrastructure development. Additionally, subsidies may support research and development (R&D) in fossil fuel technologies, helping to perpetuate competitiveness of these energy sources despite the global push for decarbonisation.
- **Consumption subsidies** aim to reduce the price paid by end-users for energy products such as gasoline, diesel, kerosene, electricity, and natural gas. These subsidies are particularly implemented as universal price support mechanisms to shield consumers from international price volatility and inflationary pressures. While well-intentioned as a social safety net, such policies often prove fiscally burdensome, regressive, and inefficient. Wealthier households, which consume more energy, tend to capture a larger share of these subsidies.

Similar mechanisms not only strain government budgets but also discourage investment in energy efficiency and renewable energy alternatives. Moreover, by distorting market signals, they can delay the transition to more sustainable energy systems.

Economic Impacts

Fossil fuel subsidies can severely distort fiscal balances by consuming a disproportionate share of public budgets, often at the expense of critical development priorities such as health care, education, and infrastructure investment. By allocating large amounts of state resources to maintain artificially low energy prices, governments crowd out more productive and equitable public expenditures, thereby undermining long-term economic growth and social development. Additionally, fossil fuel subsidies often skew investment decisions, incentivising capital-intensive over labour-intensive industries. The misallocation of resources leads to inefficient industrial structures, with subsidies favouring sectors that consume high levels of subsidised energy, rather than those that maximise employment or innovation potential. Moreover, by distorting price signals, energy subsidies encourage overconsumption and energy inefficiency across all sectors of the economy. Artificially low energy prices reduce the incentive to conserve fuel, adopt cleaner technologies, or invest in energy-efficient practices. In energy-intensive industries, these subsidies create artificial competitive advantages for firms with high consumption patterns, thereby discouraging innovation and the adoption of advanced technologies that could otherwise improve productivity and environmental performance. This is particularly true where innovative alternatives to satisfy a need with less energy intensive products exist.

In oil-exporting countries, subsidised domestic fuel prices present additional fiscal challenges. While such subsidies are often politically popular, they contribute to revenue losses and reduce fiscal space available for public investment. When international oil prices fluctuate, the fiscal burden of maintaining subsidies can escalate rapidly, especially in economies where fuel imports are significant. This dynamic not only contributes to rising energy import bills but also weakens the country's balance of payments position.

The fiscal, environmental, and welfare impacts of energy subsidy reform are potentially enormous. The IMF estimated that eliminating post-tax subsidies in 2015 could have raised government revenue by $2.9 trillion (3.6 percent of global GDP), cut global CO_2 emissions by more than 20%, and cut pre-mature air pollution deaths by more than half. After allowing for the higher energy costs faced by consumers, this action would have raised global economic welfare by $1.8 trillion (2.2% of global 2015 GDP). These savings could have been reallocated toward pro-poor spending, including targeted cash transfers and infrastructure investments that support inclusive economic growth. Furthermore, by discouraging the use of energy-efficient appliances, vehicles, and industrial processes, subsidies hinder countries' progress toward sustainable development and climate targets.

Environmental Impacts

Fossil fuel subsidies represent a significant barrier to achieving global environmental sustainability and economic efficiency. By artificially lowering the price of fossil energy sources such as coal, oil, and natural gas, these subsidies incentivise higher levels of consumption than would otherwise occur under "free" market conditions. This, in turn, exacerbates the emission of greenhouse gases (GHGs), contributes to air and water pollution, and accelerates the degradation of ecosystems and global warming effects.

According to the IEA, the removal of fossil fuel subsidies could lead to a substantial reduction in global carbon dioxide (CO_2) emissions. The IEA projects that phasing out these subsidies could result in a roughly 10% reduction in CO_2 emissions by 2030. This would represent a critical contribution toward fulfilling the mitigation goals set forth in the Paris Agreement, which aims to limit global warming to well below 2°C above pre-industrial levels, with efforts to cap the temperature increase at 1.5°C.

In addition to global environmental implications, fossil fuel subsidies have pronounced local effects. By encouraging higher consumption of polluting fuels, subsidies contribute to poor air quality, particularly in urban areas. This has direct public health consequences, as exposure to pollutants like fine particulate matter (PM2.5) and nitrogen dioxide (NO_2) is associated with respiratory diseases, cardiovascular conditions, and premature mortality. Furthermore, these subsidies often lead to inefficient allocation of resources by diverting public funds away from critical sectors such as healthcare, education, and infrastructure development.

Critically, fossil fuel subsidies are also regressive in nature. As a result, they can exacerbate income inequality while failing to address energy poverty effectively. A more equitable and efficient alternative would involve redirecting these public expenditures toward targeted social programmes or clean energy investments that offer broader societal benefits.

The perpetuation of fossil fuel subsidies, hence, poses a significant threat to both environmental sustainability, economic rationality and social equity. Phasing out these subsidies is not only a necessary step to reduce greenhouse gas emissions and meet international climate commitments, but also an opportunity to reallocate public resources in a manner that promotes social equity, economic efficiency, and long-term ecological resilience.

Case Studies: Countries That Have Reformed Energy Subsidies

Indonesia

Indonesia represents a significant and instructive case of energy subsidy reform, particularly in the context of developing and resource-rich economies. Historically a net oil exporter, Indonesia became a net oil importer in the early 2000s, a shift that exposed it to greater vulnerability from global oil price volatility.

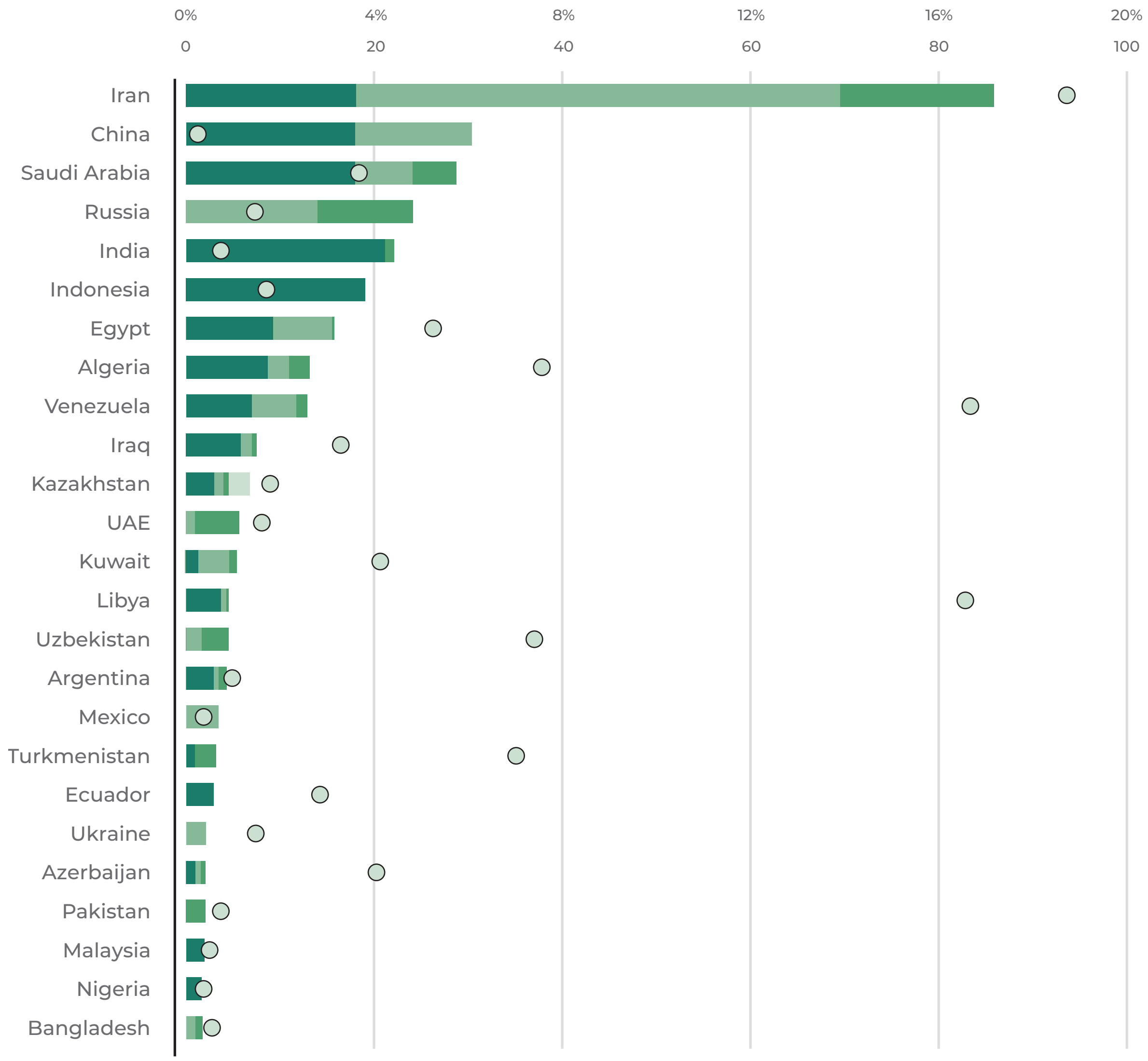


Figure 2: Value of fossil-fuel subsidies by fuel in the top 25 countries, 2020

Despite this, the country maintained substantial subsidies on petroleum products for decades, which placed considerable strain on its national budget and distorted energy consumption patterns.

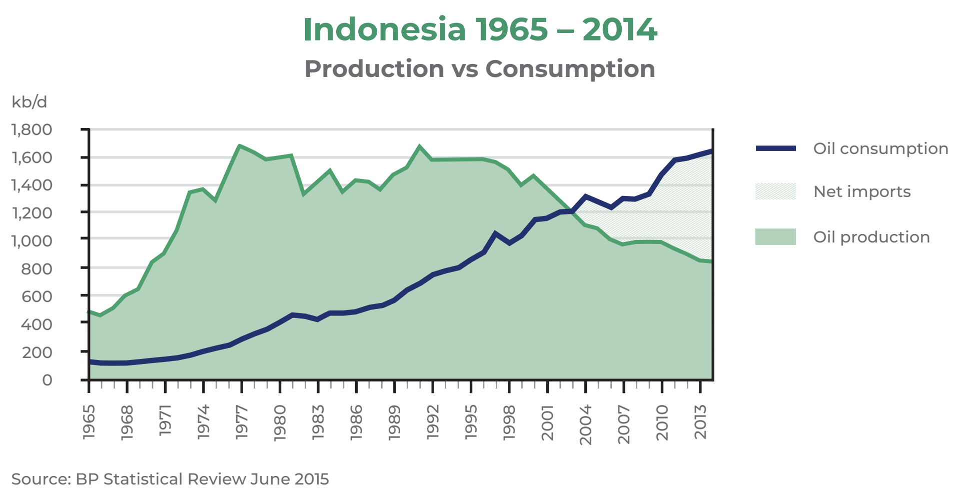


Figure 3: Indonesia Oil Import Vs Consumption

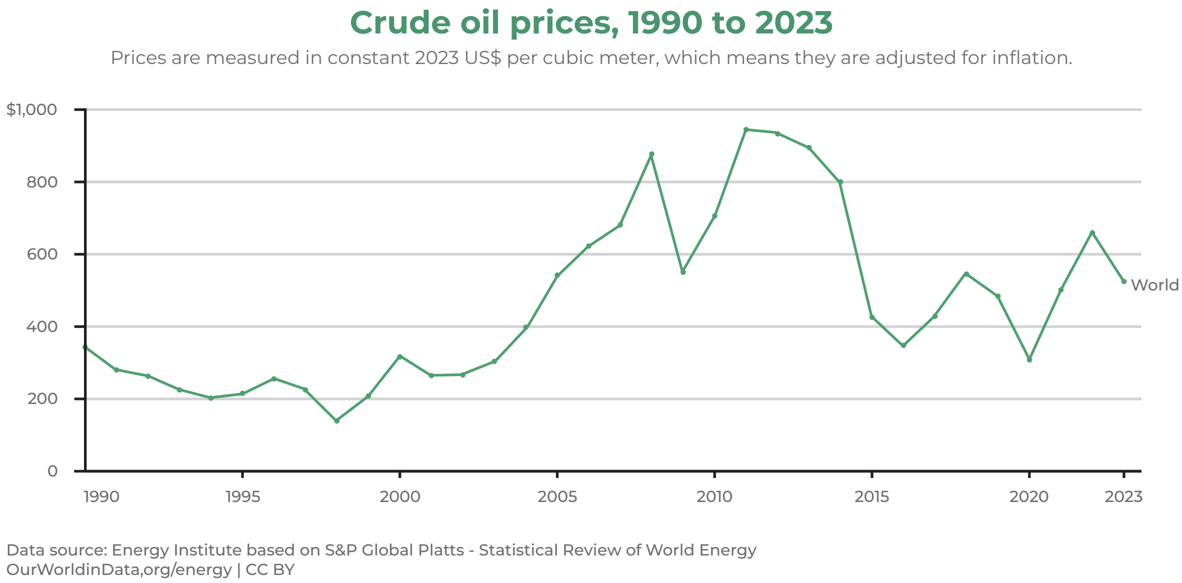


Figure 4: World Crude Oil Prices Adjusted to Inflation (1990-2023)

Historical Context and Early Reform Attempts

Efforts to reduce subsidies in 1998 and 2003 were met with widespread public protests and social unrest, compelling the government to reverse the price hikes. These initial failures underscored the complexity of energy subsidy reforms, particularly in countries where such subsidies are perceived as a form of social welfare or entitlement. The global surge in oil prices between 2003 and 2004 further exacerbated the fiscal burden, with Indonesia's petroleum product subsidies reaching approximately 5% of GDP.

The government's attempt to freeze domestic fuel prices during this period significantly worsened the budget deficit. The World Bank has also documented various efforts that were made to provide compensation to the poor during these reform attempts, including the subsidisation of rice and spending on health, education and social welfare. However, spending on such initiatives was not high during these years, (US$300 million and US$510 million having been committed in 2002 and 2003, respectively) and in 2003 many of the announced compensation programmes did not materialise.

Table 1: Gasoline, Diesel and Kerosene Household Retail Price Changes Between 1998 and 2003 (IDR/Litre)

	May 16, 1998	Oct 2000	June 2001	Jan 2002	Dec 2002[a]	Jan 2003	Mar 2003
Premium-brand Gasoline	1,000	1,150	1,450	1,550	1,750	1,810	1,810
Solar-brand Diesel	550	600	900	1,150	1,550	1,890	1,650
Kerosene	280	350	400	600[a]	n.d.	n.d.	n.d.

Source: International Institute for Sustainable Development (IISD), Lessons Learned from Indonesia's Attempts to Reform Fossil-Fuel Subsidies

The 2005 Reform Breakthrough: A Comprehensive Strategy

A breakthrough occurred in 2005 under the leadership of President Susilo Bambang Yudhoyono. The administration implemented two substantial price increases for gasoline, kerosene, and diesel, cumulatively amounting to an increase of at least 150%. Notably, the public did not resist these reforms as strongly as seen in earlier attempts. Several factors contributed to this unexpected success, including the perceived legitimacy and credibility of the newly elected government. Crucially, the second round of price increases in August 2005 was strategically linked to a comprehensive social protection programme. This included a targeted, unconditional cash transfer scheme (BLT - Bantuan Langsung Tunai) designed to mitigate the impact on vulnerable populations. The cash transfer scheme targeted roughly 15.5 million poor and near-poor households (some 28% of the population). The transfers, quarterly payments of about US$ 30 per household, continued for one year. For poor recipients the cash transfers more than compensate for the fuel price increase. Even with moderate mistargeting, (with cash benefits randomly distributed to the poorest 40% rather than the initial targeted 28% of the entire population), the programme prevented an increase in poverty due to the fossil fuels price increase.

Table 2: Gasoline, Diesel and Kerosene Household Retail Price in 2005 (IDR/Litre)

	Jan 2005	Mar 2005	Dec 2005
Premium-brand Gasoline	1,810	2,400	4,500
Solar-brand Diesel	1,650	2,100	4,300
Kerosene	700	700	2,000

Source: International Institute for Sustainable Development (IISD), Lessons Learned from Indonesia's Attempts to Reform Fossil-Fuel Subsidies

Approximately one-quarter of the savings from reduced fuel subsidies were allocated to this direct transfer programme, while the remainder funded education grants, basic healthcare services, and village-level development initiatives. According to Resosudarmo, who employed a Computable General Equilibrium (CGE) model to assess the distributional effects of the reform, the cash transfers more than offset the price increases for the poorest households, thereby enhancing the progressivity of the policy.

Communication, Monitoring, and Adjustment Mechanisms

Public communication played an essential role in the reform's success. The government launched a multifaceted awareness campaign through national newspapers, television talk shows, community bulletin boards and brochures. These efforts were aimed at enhancing transparency and building trust in the reform process. The cash transfers were distributed in two tranches, allowing the government to rectify implementation issues in real time. Feedback from public hearings and beneficiary consultations informed improvements in logistics, such as more efficient payment procedures via post offices and better complaint resolution mechanisms. Despite these initial successes, subsequent global oil price increases compelled the government to freeze fuel prices from late 2005 to mid-2008. This decision reinstated substantial fiscal burdens, especially as the wealthier segments of society, who disproportionately benefited from the subsidies, resisted further reform. Nevertheless, in May 2008, the government again raised fuel prices by more than 25%, introducing another wave of targeted cash transfers to mitigate social impacts. The Indonesian budget had been drawn up assuming a price of US$95 a barrel while the U.S. light sweet crude price peaked at

Table 3: Gasoline, Diesel and Kerosene Subsidies (1999–2008)

Year	Volume of fuel[1]	Subsidies	
	(billion litres)	(trillion IDR)	(billion US$)
1999	n.a.	39.5	4.3
2000	n.a.	55.6	6.1
2001	48.7	61.8	6.8
2002	49.6	31.6	3.5
2003	50.5	31.7	3.5
2004	50.2	72.9	8
2005	49.5	39.8	4.4
2006	37.5	67	7.4
2007	38.6	87.6	9.6
2008 (estimate)	35.8	160[a]	17.6

Source: Laan, T. And Dillon, H.S., Biofuels – at What Cost? Government Support for Ethanol and Biodiesel in Indonesia

US$147.27, causing subsidy spending to balloon from the US$5 billion that had been planned, to an estimated US$17.6 billion.

Fuel prices rose on average by 28.7% and the moves were, once again, accompanied by a cash transfer programme to compensate poor households for increases to their living costs, this time for a total of US$1.52 billion. In September and November 2009, the Group of Twenty (G-20) and the Asia-Pacific Economic Cooperation (APEC), both of which count Indonesia as a member, committed to phase out and rationalise inefficient fossil-fuel subsidies that lead to wasteful consumption, nevertheless, the national reform momentum faced renewed challenges in 2010, when the government signalled a retreat from further fuel price increases and instead planned for higher fuel subsidy allocations in the national budget.

Recent Developments and Ongoing Challenges

In 2014, taking advantage of lower international oil prices, the Indonesian government initiated a new bold policy shift by eliminating gasoline subsidies and introducing automatic price adjustments for diesel. At that time, subsidies consumed up to 20% of the national budget, crowding out critical investments in social infrastructure. In November 2014, a one-off 34% average gasoline and diesel price increase was enforced. The reforms freed up fiscal space for targeted expenditures in health, education, and infrastructure, thereby reinforcing inclusive growth and sustainable development.

The new fuel subsidy scheme, effective on 1 January 2015, was expected to have positive impacts on fiscal management and the economy such as reducing budget uncertainty, reducing fuel subsidy spending, safeguarding fiscal sustainability, expanding fiscal space for other spending, and lowering the inflationary impact. The government implemented this policy inconsistently before eventually reversing it. In practice, the frequency of fuel price adjustments continuously changed; from every two weeks to every month, to every three months in 2015, and did not change at all since 2017.

Without institutionalising an automatic and rigorous fuel pricing mechanism, Indonesia remains susceptible to cycles of politically motivated price freezes, fiscal imbalances, and reactive policy interventions during periods of oil price volatility. In fact, according to the World Bank, in June 2022 the case for eliminating or better targeting the subsidies remains still strong. The explicit and implicit fuel subsidies were still largely benefiting the local middle and upper class. Furthermore, Jakarta continued to subsidies Coal, Natural Gas and Power through out several national producers and distributors.

The Last (for Now) Attempt to Pave the Way for a Definitive Liberalisation of the Fossil Fuel Sector

On 15 November 2022, Indonesia and a group of nations led by the United States announced a $20 billion climate finance deal to curb its power sector's reliance on coal, and transition towards a carbon-free energy system. This deal was officially called the Just Energy Transition Partnership (JETP). A year later, Indonesia released implementation plans for the agreement, outlining numerous targets and policies to help the country achieve carbon neutrality and grow its domestic renewable technology industry. However, none of the recommended policies address the most significant threat to Indonesia's energy transition: fossil fuel subsidies.

On 21 November 2023, the government of Indonesia released a draft implementation plan outlining its strategy to utilise the support provided by the JETP. The draft implementation plan, formally known as the Comprehensive Investment and Policy Plan (CIPP) and the "policy enablers" it includes, do not sufficiently alter Indonesia's subsidy regime. Instead, Indonesia's government outlines policies that in the CIPP simply attempt to address the anti-competitive effects of these subsidies. This is a significant weakness, as much of the funding for new renewable generation must come from the private sector. Few private sector companies will invest in renewable energy projects in a non-competitive market.

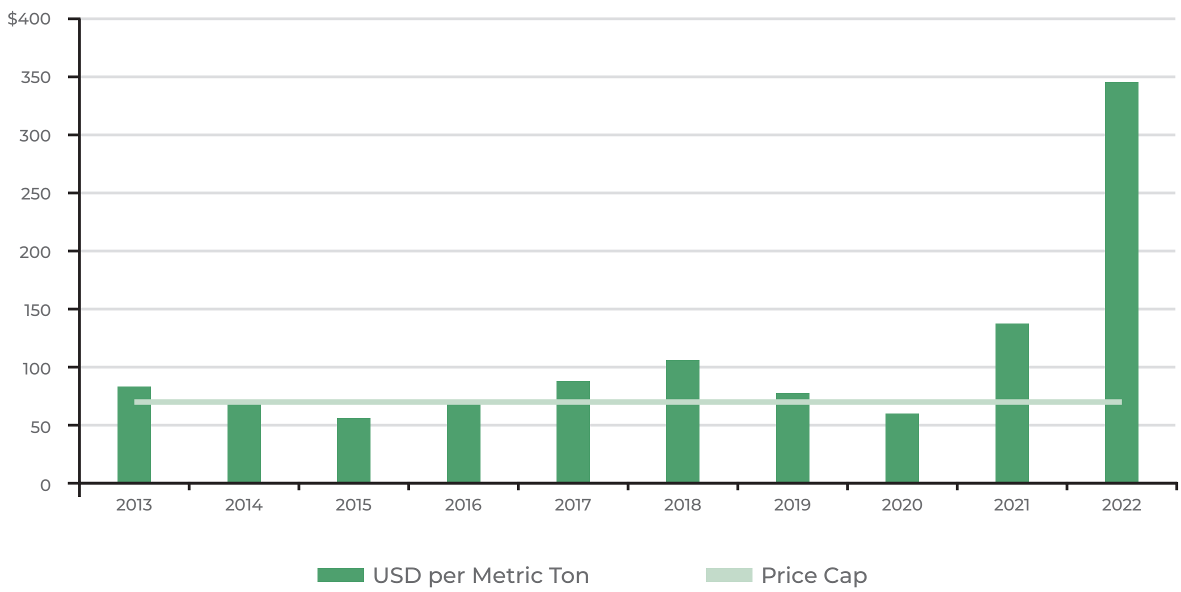


Figure 5: Price of Thermal Coal Vs $70 Domestic Price Cap per Metric Ton (Source: The Diplomat (2024) Indonesia's fossil fuel subsidies threaten its energy transition)

Success Factors in Indonesia's Fossil Fuel Subsidy Reform

Despite its lengthiness and its incompleteness, Indonesia's experience with fossil fuel subsidy reform is frequently cited as a notable example of effective policy implementation in a developing country context. A combination of strategic planning, institutional commitment, and public engagement contributed significantly to the relative success of the reform measures introduced in the mid-2000s and again in 2008, 2014 and 2023. Among the most important enabling factors the following should be mentioned:

- Strong political will although this varied over the years depending on the popularity of the leaders in charge, endogenous factor, and on the international price of crude oil, exogenous factor
- Effective communication with the public (probably the most remarkable success of the entire reform)
- Reallocation of savings to visible social programmes
- Market-based pricing mechanism overseen by independent bodies. This has not always been the case in Indonesia, prompting the chronological discontinuity in the liberalisation measure and preventing the governments to demonstrate to citizens that fuel prices are dictated by international forces, not the local government.

All these elements played a role in achieving the overall results so far. As pointed out in the previous lines, the liberalisation reform is not fully complete, but it is undeniable that the government recognised the need to move away from most of the subsidies.

Ghana

Historical Context

Ghana's engagement with oil and gas subsidies dates back several decades, characterised by government interventions to control fuel prices and ensure affordability. As in other countries, the subsidies aimed to protect consumers from international price fluctuations and support economic activities reliant on petroleum products. However, by the early 2000s, the sustainability of these subsidies came into question. The financial strain on the government's budget, coupled with inefficiencies in the subsidy distribution, highlighted the need for reform. The Institute of Development Studies (IDS) notes that fossil-fuel subsidies in Ghana were an inefficient means of protecting the incomes of poor households, with a larger proportion of benefits accruing to higher-income groups.

Policy Reforms and Deregulation Efforts

Recognising the challenges posed by fuel subsidies, Ghana initiated a series of reforms aimed at liberalising the petroleum sector. Key milestones in this journey included:

- **2001:** The Ghanaian government attempted to liberalise its fuel prices as part of an IMF Poverty Reduction and Growth Facility Program through the introduction of an automatic price adjustment formula to align domestic fuel prices with international market trends. However, rising global oil prices towards the end of 2002 put pressure on the government to discard the price setting mechanism.
- **2003:** Reintroduction of the pricing mechanism, resulting in significant fuel price increases. This led to wide public opposition and in a subsequent retraction of the fuel pricing mechanism. The total cost of fuel subsidies in 2004 amounted to 2.2% of Gross Domestic Product (GDP); however, a further 1% of GDP was also required to support the operation of the state-owned Tema Oil Refinery (TOR).
- **2006:** Fossil-fuel subsidies continued to be a significant drain upon Ghana's budget. To address this, a new tack was taken. This third attempt at fossil-fuel subsidy reform was centered upon the creation of a pricing mechanism that kept domestic prices in line with international prices; this was controlled by an independent governing body, the National Petroleum Authority (NPA).
- **2015:** Implementation of full price deregulation, allowing market forces to determine fuel prices. The Major Oil Marketers Association of Nigeria (MOMAN) highlights that the 2015 deregulation also aimed at a full liberalisation, to entirely remove government control over the importation of crude oil and refined products, establishment of facilities, on top of price controls.
- **2023-24:** Increased competition, especially in the downstream sector. In fact, since the deregulation policy in 2015, Bulk Distribution Companies (BDCs) have grown from 31 to 53 in 2024, while Oil Marketing Companies (OMCs) have surged from 139 to over 200.

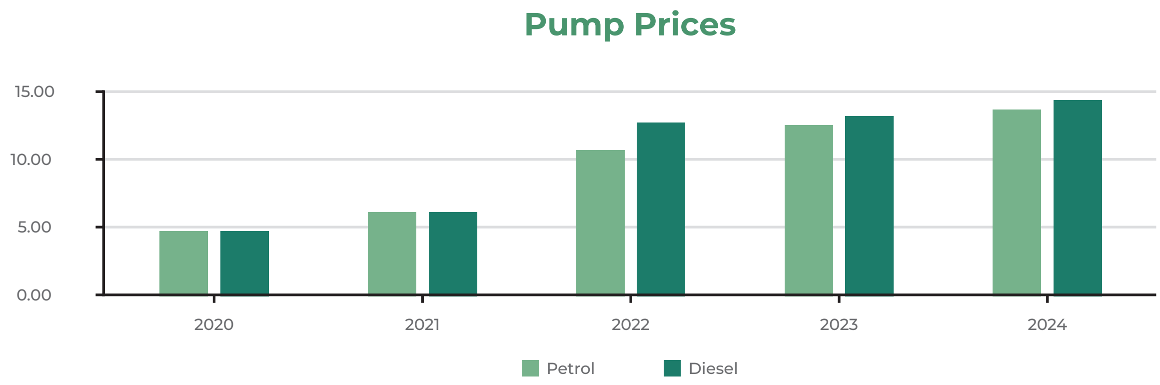


Figure 6: Pump Prices in Ghana (2020-2024) for Gasoline and Diesel

Economic Implications of Subsidies Removal

The removal of fuel subsidies had profound economic impacts (positive and negative):

- **Green Paradox:** The results of changes, (measured in USD million) due to imported refined oil subsidy removal, might lead to welfare losses where the benefits accruing from environmental cleanup are not considered and the subsidy removal does not offset other pre-existing distortions. Consequently, according to Presley K. Wesseh Jr., Boqiang Lin and Philip Atsagli, the removal of imported refined oil subsidy in 2007 in Ghana led to a $ 935.24 million welfare loss. Accounting for environmental benefits would still result in welfare losses, but by a lesser value, that is, $ 337.8 million due to the constant increase in consumption of fossil fuels i.e. rigid demand, (and related GHG emissions) even after the liberalisation period.
- **Fiscal Relief:** Reducing subsidies alleviated the financial burden on the government's budget, freeing resources for other developmental priorities.
- **Market Efficiency:** Deregulation fostered competition among petroleum service providers, leading to improved efficiency and service delivery.
- **Inflationary Pressures:** Initial subsidy removal led to fuel price hikes, contributing to inflation and increased cost of living.
- **Lack of Investment in low carbon energy technologies:** The existence of fossil-fuel subsidies in many middle-income countries like Ghana, effectively results in 'negative' carbon pricing, restricting the potential for much needed investment in low carbon energy technologies.

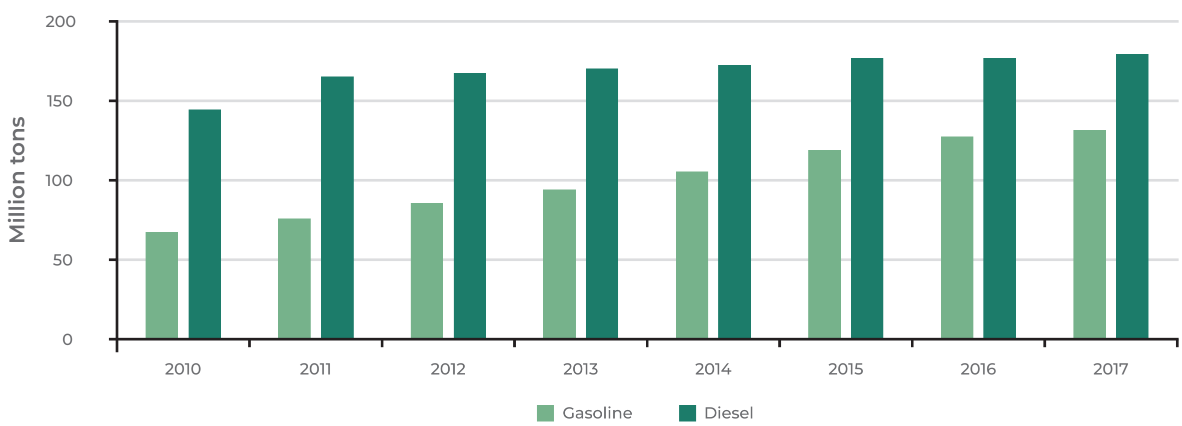


Figure 7: Statistic Gasoline and Diesel Consumption in Ghana from 2010 to 2017. (Source: Liu, S., Chen, W., Zhu, Z., Jiang, S., Ren, T. and Guo, H. (n.d.) A Review of the Developed New Model Biodiesels and Their Effects on Engine Combustion and Emissions)

Table 4: Total Final Energy Consumed by Fuels (in ktoe between 2000 and 2023)

Year	Electricity[1]		Petroleum[2]		Biomass		Total
	Ktoe	%	Ktoe	%	Ktoe	%	Ktoe
2000	591	10.8	1,445	26.4	3,432	62.8	5,468
2001	614	11.5	1,467	27.6	3,238	60.9	5,319
2002	586	11.2	1,550	29.7	3,082	59.1	5,218
2003	449	9.2	1,494	30.7	2,925	60.1	4,868
2004	458	9.2	1,705	34.1	2,839	56.8	5,002
2005	513	10.3	1,712	34.4	2,745	55.2	4,970
2006	623	12.3	1,775	35.0	2,671	52.7	5,069
2007	532	10.3	2,023	39.1	2,614	50.6	5,170
2008	601	11.7	1,973	38.6	2,544	49.7	5,118
2009	618	11.0	2,496	44.4	2,513	44.7	5,627
2010	667	12.2	2,408	44.0	2,395	43.8	5,471
2011	765	13.0	2,704	45.9	2,419	41.1	5,889
2012	851	12.9	3,189	48.3	2,566	38.8	6,606
2013	908	12.9	3,308	47.1	2,804	39.9	7,020
2014	917	13.1	3,243	46.2	2,853	40.7	7,013
2015	829	11.5	3,497	48.4	2,896	40.1	7,222
2016	993	13.8	3,255	45.3	2,945	40.9	7,193
2017	1,058	14.7	3,104	43.0	3,053	42.3	7,214
2018	1,166	14.9	3,581	45.8	3,063	39.2	7,809
2019	1,209	15.4	3,793	46.7	3,062	37.8	8,114
2020	1,370	15.9	4,248	49.1	3,026	35.0	8,644
2021	1,502	17.1	4,640	52.7	2,660	30.2	8,802
2022	1,562	17.7	4,317	48.9	2,946	33.4	8,826
2023	1,621	17.8	4,641	51.0	2,845	31.2	9,107

1 Includes commercial losses
2 Petroleum consumption from 2016 onwards includes natural gas used in industry
Source: Energy Commission of Ghana 2024

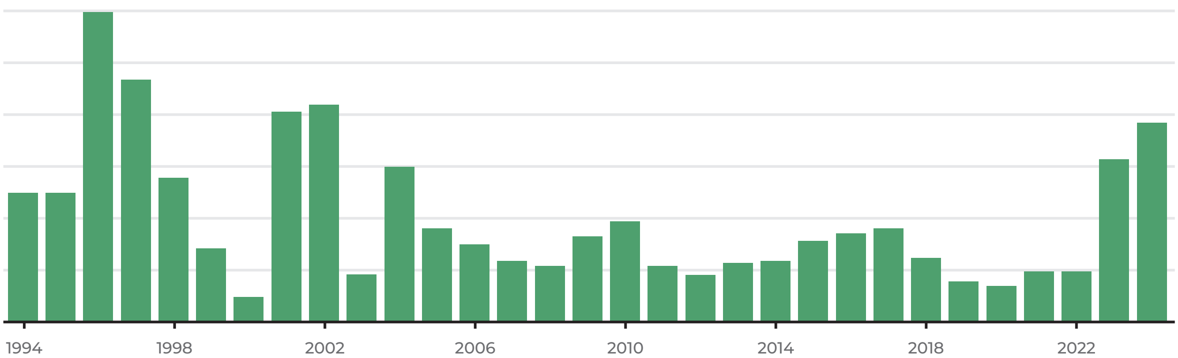


Figure 8: Consumer Price Index (1994-2024) (Source: Macrotrends: Ghana consumer price index)

The Energy Sector Management Assistance Program (ESMAP) underscores that while subsidy reforms can lead to economic efficiency, they must be carefully managed to mitigate adverse effects on vulnerable populations and cannot prescind from the parallel implementation of policies aimed at stimulating economic activities and reducing the level of CO_2 emissions.

Social and Environmental Considerations

Beyond economic factors, subsidy reforms have social and environmental dimensions:

- **Equity Concerns:** Subsidy removal might disproportionately affect low-income households, necessitating targeted social protection measures.
- **Reparatory measure:** The savings from subsidies on fossil fuels should be invested in social protection measures such as: A) removal of fees for state-run secondary and primary schools; B) ceiling the fares for public transport; C) increase spending to deliver healthcare to the poorest areas of the country; D) greater focus on the electrification of the rural areas. All those measures were implemented in Ghana starting from 2005 as forms of social compensation to counterbalance the increase of fuel prices.
- **Environmental Benefits:** As seen, reducing fossil fuel subsidies can lead to decreased greenhouse gas emissions, contributing to climate change mitigation efforts but this is not an automatic cause-effect relation. It is though paramount to invest part of the subsidies savings in economic activities, sectors and technologies aimed at GHG reduction and environmental footprint abatement. An IEA (2011) report estimated that, relative to the year baseline, the phasing out of fossil-fuel consumption subsidies by 2020 would have led to 5% greenhouse gas (GHG) emissions reduction.
- **International Support and Cooperation:** The limited financial capacity of developing countries means that international support is required creating a cooperation network in various sectors of social and economic fields.
- **Subsidy reform is gradual:** The reforms in Ghana occurred at a relative fast pace; this meant that the repercussions of reform were felt quickly. Although it may not always be feasible, gradual fossil-fuel subsidy reform may offer a means of reducing public opposition and are preferable in a stable political and social context.

The Political Aspect

The preceding analysis of the Ghana case demonstrated that the removal of fossil fuel subsidies might contribute meaningfully to low-carbon climate-resilient development (LCCRD). However, its implementation is highly susceptible to shifts in political dynamics. In fact, efforts to facilitate the removal of subsidies have yielded only limited and short-term success in Ghana. The effectiveness of pricing mechanisms has been contingent upon sustained political commitment. In practice, governments often intervene in fuel pricing for political purposes, undermining the stability of such regimes. Establishing a fully autonomous pricing authority remains a significant challenge, as regulatory decisions can be overridden and legislation amended at the discretion of political actors. To mitigate these risks, it is essential to adopt a pricing framework that automatically aligns domestic fuel prices with international market trends as long as it is under a defined ceiling or measures are in place to mitigate the negative social impact on the many people, without resorting to cross-subsidisation of different products. This approach is crucial to insulating fuel pricing from political interference and ensuring long-term policy credibility.

The Challenge of Removing Subsidies While Protecting Vulnerable Populations

Political Economy of Subsidies

Subsidies are often maintained due to entrenched vested interests, rent-seeking behaviour, and the considerable political costs associated with their removal. Their regressive impact is frequently obscured by the universality of their coverage, which gives the impression of equitable distribution.

Fossil fuel subsidies tend to be politically entrenched. They are commonly perceived as mechanisms to secure public support and to appease influential interest groups. Governments often justify these subsidies as necessary tools for protecting the economically vulnerable; however, empirical evidence indicates that such benefits disproportionately accrue to wealthier households, which typically consume more energy. Efforts to reform fossil fuel subsidies often provoke significant public resistance and political backlash. The fact is that fossil fuel subsidies are heavily influenced by the political consensus of the local political leadership. Some countries have nonetheless pursued reforms aimed at improving the efficiency of natural resource use and reducing the GHG emissions. For instance, reducing energy subsidies has been shown to incentivise more efficient agricultural water use and to promote the adoption of water-saving technologies in India.

Distributional Impacts

Subsidies often deliver greater benefits to higher-income households, particularly in low-income countries where the poorest segments of the population frequently lack access to subsidised utilities such as electricity or running water. While poor people receive some of these benefits, overall, the benefits are skewed to wealthier groups and often dwarf more progressive public expenditure. Fuel subsidies alone are 2 to 7.5 times as large as public spending on health in Bangladesh, Ecuador, Egypt, India, Indonesia, Morocco, Pakistan, Turkmenistan, Venezuela, and Yemen. At the same time, subsidies encourage inefficient, carbon-intensive use of energy and build constituencies for this inefficiency. Incidence analyses have demonstrated that gasoline and diesel subsidies tend to be regressive, while subsidies for kerosene (used for domestic lamps in rural areas) may be more neutral in their distributional impact, but still inefficient from an environmental standpoint.

Despite being framed as instruments for promoting social equity, fossil fuel subsidies are regressive in practice. Although removing such subsidies can release valuable fiscal resources for alternative uses, it also leads to increased living costs, particularly in sectors such as transportation and food. To mitigate these impacts, governments must proactively address distributional concerns by implementing compensatory mechanisms. These may include targeted cash transfers or the strengthening of social safety nets, which help cushion vulnerable populations against the negative consequences of subsidy reform.

Strategies for Managing the Transition

As demonstrated by the concrete experience in several countries around the world, energy price reform can endanger poor people and arouse the opposition of pressure groups used to benefit from low prices, thereby posing political risks and opposition to the local governments. Having said that, failure to reform the subsidies towards liberalisation can be worse, diverting public funds from investments that fight poverty, and fostering an inefficient economy increasingly exposed to energy shocks. Consensus might be obtained through a gradual approach, i.e. reforms need not to be undertaken overnight and through effective compensation actions.

In fact, several policy tools have demonstrated efficacy in facilitating a socially and politically viable transition:

- **Gradual Phase-Out:** Implementing reforms incrementally allows households and industries to adapt over time.
- **Compensatory Transfers:** Well-designed and targeted cash transfers can offset the burden of increased prices on low-income groups.

- **Public Communication:** Transparent and inclusive communication regarding the objectives and anticipated benefits of reforms can enhance public acceptance.
- **Institutional Strengthening:** Developing robust administrative structures is essential for effectively targeting and delivering subsidies.
- **Monitoring, evaluation and feedback:** Tracking impact, communicating benefits and using feedback to adjust policies

On top of the experiences in Indonesia and Ghana, a notable example of a balanced reform is Egypt's progressive removal of electricity and fuel subsidies. The Egyptian government complemented these efforts with substantial investments in social welfare programmes, thereby mitigating the adverse social consequences of the reform process. Energy subsidies reform allowed for increasing public spending in education, health, and social protection sectors, aiming at improving human capital.

How Subsidies Influence Investment Decisions in Renewables vs. Fossil Fuels

Market Distortions and Investment Risks

The continued subsidisation of fossil fuels also introduces significant policy risks for the renewable energy sector. When fossil fuels are maintained at artificially low prices, the financial returns on renewable energy investments become less attractive, discouraging both foreign and domestic direct investment (FDI) in clean technologies. This dynamic hinders capital mobilisation for renewables and slows the pace of global energy transition. As highlighted by the International Renewable Energy Agency, subsidies that favour fossil fuels disproportionately disadvantage emerging renewable markets, exacerbating the challenge of achieving climate targets.

The Levelized Cost of Energy (LCOE) Argument

The Levelized Cost of Energy (LCOE) serves as a key metric in assessing the economic viability of different energy sources. While wind and solar energy have become increasingly cost-competitive over the last decade, the presence of fossil fuel subsidies skews this metric by distorting relative price comparisons, thus inhibiting the market penetration of renewables. For instance, the IEA reports that global investment in clean energy must more than triple by 2030 to remain on track for net-zero emissions. However, fossil fuel subsidies continue to divert resources toward legacy technologies, thereby impeding progress. Further research by the International Monetary Fund (IMF) corroborates these concerns, noting that fossil fuel subsidies not only result in inefficient allocation of public resources but also inhibit innovation and cost reductions in the renewable energy sector.

Crowding Out Renewable Incentives and Impact on Investor Behaviour

Beyond market distortion, fossil fuel subsidies erode governmental fiscal capacity to support renewable energy initiatives. The diversion of public funds to subsidise fossil fuels constrains the ability of governments to finance mechanisms such as feed-in tariffs, tax incentives, and research and development (R&D) programmes tailored to renewables. This not only delays the broader decarbonisation agenda but also undermines energy security by failing to foster a diversified energy mix. Countries such as Germany and Denmark have achieved remarkable progress in renewable energy deployment, in part due to their conscious policy decisions to phase out fossil fuel subsidies while actively investing in clean technologies. By contrast, regions that persist in subsidising fossil fuels often demonstrate stagnation in clean energy adoption, underscoring the long-term drawbacks of such policy choices. In fact, investors tend to follow price signals. Subsidies for fossil fuels create uncertainty and reduce returns on clean energy technologies. They also affect innovation and reduce financing options for green projects. Subsidy reform, such as the one promoted by the IMF, is essential for achieving global climate targets. Without reform, the marginal abatement cost of emissions reduction rises, and renewable adoption lags. Complementary policies like carbon pricing, green bonds, and R&D

incentives are crucial. High subsidiser countries, those whose diesel prices are less than half the world market rate, emit about twice as much per capita as other countries with similar income levels. Furthermore, countries with long-standing fuel taxes, such as the United Kingdom, have evolved more energy-efficient transport and water and land use. In a world facing climate urgency, energy subsidy reform is no longer optional. Policymakers must balance economic, social, and environmental imperatives by adopting integrated, evidence-based, and transparent approaches to energy policy.

Conclusion

Today, the reform of energy subsidies is no longer a policy option, it is a necessity. Phasing out fossil fuel subsidies presents an opportunity to reallocate scarce public resources toward more productive and equitable uses. It also enables the adoption of cleaner technologies, supports climate mitigation goals, and enhances social welfare. However, the path forward is fraught with challenges. Policymakers must balance short-term political risks with long-term development goals. They must design reforms that are inclusive, transparent, and evidence based. They must ensure that the transition does not leave the most vulnerable behind. Ultimately, energy subsidy reform is a test of governance, leadership, and vision. If done right, it can serve as a powerful catalyst for a more just, sustainable, and prosperous future.

05

CHAPTER 05

THE POLITICS OF THE ENERGY TRANSITION

The transition from fossil fuels to cleaner, more sustainable energy sources is not merely a technological shift; it is an inherently political process. The "energy transition" refers to the transformation of global energy systems from carbon-intensive sources like coal, oil, and gas to renewable and low-carbon alternatives such as solar, wind, and hydropower. While this shift is driven by the urgent need to address climate change, it also entails profound political, economic, and social ramifications. This chapter explores the politics of the energy transition, focusing on the influence of vested interests, geopolitical implications, social justice dimensions, and the role of governance and public policy.

The politics of the energy transition are complex, contested, and consequential. While the technical and economic feasibility of a low-carbon future is increasingly clear, the political will to realise it remains uneven. Vested interests, geopolitical shifts, social equity, and governance structures all shape the trajectory and outcomes of the transition.

This chapter critically explores relationships between concentrated and decentralised renewable energy and political power. Advocates assert that because the renewable energy transition is fundamentally a political struggle, efforts to shift from fossil fuels and decarbonise societies will not prove effective without confronting and destabilising dominant systems of energy power.

The objectives of this chapter are therefore:

1. To explore the relationships between renewable energy and political power
2. To critically assess the tensions associated with an energy democracy agenda
3. To draw out the implications for democratising renewable energy development in practice ▸

Decentralised energy-politics posits that decentralised energy sources and technologies enable and organise decentralised political power and vice versa. Efforts are underway to find ways to re-organise decentralised energy flows into aggregated and concentrated stocks of energy and other forms of political power. More democratic renewable energy futures may benefit from strengthening democratic practices and outcomes, extending democratisation of energy systems across all components, stages and end uses, and sharpening positions relative to dominant pressures of capitalism and market ideology, the ideology of unlimited growth, and the modernist/industrialist agenda. Renewable energy systems offer a possibility but not a certainty for more democratic energy futures.

Innovation is needed to develop effective alternatives—after all, we did not shift from horse to car by taxing the horses.

Climate science has long established the link between greenhouse gas emissions and global warming. The Intergovernmental Panel on Climate Change (IPCC) has made it clear that reducing carbon emissions is essential to limiting global temperature rise to 1.5°C or 2°C above pre-industrial levels[2] (IPCC, 2021). Energy production and consumption are the largest contributors to these emissions, making a transition to cleaner energy a cornerstone of climate mitigation efforts.

Beyond climate concerns, the energy transition is also motivated by technological innovation, falling costs of renewables, energy security, and economic opportunities. Yet, despite these drivers, the pace of transition varies dramatically across countries and regions due to political and institutional factors.

One of the most significant barriers to the energy transition has been the influence of entrenched fossil fuel interests. These actors—ranging from multinational oil corporations to coal-dependent economies—exert considerable political influence through lobbying, campaign financing, and regulatory capture[3] (Stokes, 2020). Governments often provide subsidies to fossil fuel industries, either directly or indirectly, undermining climate goals.

For instance, the United States has seen periods of aggressive climate denial and rollbacks of environmental regulations, especially under administrations aligned with fossil fuel lobbyists. Similarly, in petrostates like Russia, Saudi Arabia, and Venezuela, the political elite's power is tightly interwoven with oil revenues, making energy diversification a politically sensitive issue4 (Mitchell, 2011).

Geopolitical Implications

The energy transition reshapes the geopolitical landscape. Fossil fuels have long been central to global geopolitics, with oil-rich countries wielding significant power through organisations like OPEC. Control of oil has underlined the international policies of many western states. However, as renewable energy becomes more prevalent, the distribution of geopolitical power may shift as the sources of non-fossil fuels are more geographically diverse.

Countries with abundant renewable resources (e.g., sunlight, wind) and critical minerals (like lithium and cobalt used in batteries) could become new energy powerhouses. For example, China has taken a leading role in solar panel production and rare earth element refining, positioning itself strategically for the future energy economy[5] (IRENA, 2022). This shift has sparked concerns in the West about over-reliance on China for clean energy technologies.

Moreover, decarbonisation may reduce the geopolitical leverage of oil-exporting nations, potentially leading to economic instability and political unrest in regions heavily dependent on fossil fuel revenues6 (Van de Graaf & Colgan, 2017).

Policy Instruments and Governance

Effective governance is crucial for managing the energy transition. Governments must design and implement policies that promote clean energy deployment, phase out fossil fuels, and support affected stakeholders.

Key policy instruments include:

- **Carbon pricing:** Putting a price on carbon emissions through taxes or cap-and-trade systems incentivises low-carbon choices.
- **Subsidies and incentives:** Feed-in tariffs, tax credits, and renewable portfolio standards help scale up renewables.
- **Regulations:** Mandates for fuel efficiency, emissions standards, and building codes drive structural change.
- **Public investment:** Direct spending on research, infrastructure, and green job creation stimulates the clean energy economy.
- **Green Public Procurement:** Leveraging government purchasing power to buy goods, services, and works with a reduced environmental impact encourages sustainable production and drives demand for low-carbon technologies.
- **Penalising factor:** By increasing the capital requirements of banks for their exposures to projects generating negative externalities

The political feasibility of these measures depends on public opinion, institutional capacity, and political leadership. For example, Germany's "Energiewende" (energy transition) demonstrates how strong policy frameworks and civic engagement can facilitate change, although the phase-out of nuclear power and reliance on coal have complicated its climate objectives[9] (Morris & Jungjohann, 2016). In contrast, countries with fragmented governance or strong fossil fuel lobbies often face policy inertia or reversal. The lack of a global regulatory framework also hampers coordination and ambition.

The Role of Innovation

While policies and regulations are important for the energy transition, they are not sufficient. Citizens should be provided effective alternative to fossil fuel based and energy intense products, accessible and reliable, for the satisfaction of their needs. Otherwise, the enforcement of policies and regulations will face strong resistance (e.g. Yellow jackets in France). Innovation is needed to develop these alternatives and investment is needed for their deployment at scale. We did not shift from horse to car by taxing the horses.

The Role of Civil Society and Activism

Civil society organisations, environmental NGOs, and grassroots movements play a critical role in shaping the politics of the energy transition. Activism has brought climate change to the forefront of political agendas, pressured governments to act, and mobilised public support for decarbonisation. Movements like Fridays for Future, Extinction Rebellion, and divestment campaigns have influenced discourse and policymaking, especially among younger generations. Litigation is another emerging tool; climate lawsuits against governments and corporations are increasing worldwide, aiming to hold them accountable for inaction or misinformation.

Energy Transitions in Authoritarian vs. Democratic Regimes

Political systems influence how energy transitions unfold. In democratic regimes, policymaking is subject to public debate, electoral cycles, and lobbying, which can both enable and constrain bold action. While this may slow down decision-making, it can also enhance legitimacy and public support.

Authoritarian regimes, on the other hand, can implement long-term strategies without political opposition. China, for example, has invested heavily in renewables and electric vehicles as part of its centralised industrial policy. However, the absence of accountability and civil society engagement may result in environmental degradation or unjust practices, such as forced labour in supply chains.

The success of energy transitions in different systems thus depends on institutional capacity, state-society relations, and leadership priorities rather than regime type alone.

Distributed Power versus Concentrated Energy

Despite a growing sense of urgency, the deployment of renewable energy technologies has often been slowed by democratic procedures such as local consultations and permitting delays. In many cases, local conflicts around renewables energy installations, especially wind power but also solar facilities, have delayed or even halted the uptake of renewables, mirroring the many worldwide historical conflicts around the development of technologies such as hydroelectric and nuclear power. It would thus appear an unlikely and even poorly considered time to call for greater democratic engagement with the renewable energy transition. Within the past decade, however, renewable energy advocates and social and environmental justice activists have been organising around a call for energy democracy. Energy democracy can be understood as a contemporary expression of decentralised grassroots movements of the 1970s, the 1980s and before. These earlier movements frequently sought to connect antinuclear activism and concerns about the geopolitical instability of fossil fuels with calls for local direct action and visions of "technological democracy".

The origins of the present discourse around energy democracy can be traced to various activist communities within Europe and the United States who have been developing an explicit energy democracy agenda for nearly ten years. The term and notion of 'energy democracy' has since been taken up among climate justice activists, some trade unions and academics, and political parties, and put into practice through project-level, municipal, regional and national experiments.

Compared to fossil fuels, renewable energy offers many perceived advantages in addition to fuel switching, including the relative availability of distributed renewable resources, the access to and modularity of their enabling technologies, and the potential for new forms of ownership. These advantages have inspired a movement committed to advancing social and environmental justice through a transition toward renewable energy technologies. These efforts are seen as an extension of various, widespread social movements working to address climate and economic crisis by not only resisting fossil fuel use and a market-driven green economy agenda but also by advocating for decentralised, democratised, and community-based renewable energy futures. This approach calls for reclaiming the energy sector and shifting political power to workers, households, communities, and the public, in opposition to a centralised, corporate, utility-scale renewable energy model. Some leading organisations explicitly promoting energy democracy include the Local Clean Energy Alliance, Trade Unions for Energy Democracy, the Institute for Local Self Reliance and the Centre for Social Inclusion, Transnational Institute. The Rosa Luxemburg Stiftung, or Rosa Luxemburg Foundation, also promotes energy justice, energy sovereignty, energy citizenship, and energy decolonisation that similarly integrate political claims within agendas for energy transitions.

Energy democracy as yet defies specific definition; while a multitude of priorities are embraced within the movement, several commonalities hold the energy democracy agenda together. Energy democracy is a part of the process of ongoing struggles for economic and political democratisation as expressed through the practical project of energy transitions. Seeing opportunity in renewable energy technologies, especially solar and wind technologies, energy democracy targets energy systems as key sites of political-economic contests, shifting power over diverse aspects of these sectors, including generation, distribution, finance, technology and knowledge, and pursuing a goal of high levels of deployment of renewable energy. Energy democracy seeks to empower low-income communities and communities of colour, embracing the idea that those most marginalised are well-positioned to envision and lead toward different energy futures.

The energy democracy agenda seeks to advance democratisation and participation through democratically planned and public- and community-owned and -operated renewable energy systems that serve the public interest and deliver tangible community benefits, such as decent and stable employment, public space and transportation, and new public institutions. Energy democracy eschews not only centralised commodity-based energy models based on fossil fuels and nuclear energy but also historical inequalities, neoliberal ideologies, alliances with large corporate profit interests, privatisation, market-driven and growth-based approaches and concentrations of economic and political power. Energy democracy also means ensuring fair access to energy, taking responsibility for the quality of ecological systems, and changing attitudes about energy consumption toward conservation and sufficiency. Ultimately, energy democracy redefines individual consumers as citizens, energy commodities and provisions as public goods, and infrastructure as public works or common resources.

Energy democracy and energy transitions are also fundamentally political. Given the seemingly pervasive grip that fossil fuel industries and their financial and political allies command over contemporary political life, energy democracy activists seek to make visible within the public sphere the hidden infrastructures, privatised decisions and distant consequences of modern energy systems. The instinct to politicise renewable energy transition reflects an implicit understanding that the transition from fossil-fuel dominant systems to those based on renewables offers an unprecedented yet potentially unrepeatable opportunity. As with new forms of media communications, new energy technologies present an opportunity to more deeply engage with questions of technological determinism. Through selection and construction of these large-scale infrastructural technologies, the world will again be re-ordered: decisions and investments will be made, groups of actors will be politically re-positioned, and material structures as well as social and ecological

Energy democracy seeks to empower low-income communities and communities of colour, embracing the idea that those most marginalised are well-positioned to envision and lead different energy futures.

patterns will be established that may endure for generations. The form of politics used to steer renewable energy transitions will greatly influence the possibility for more democratic futures.

In other words, if governed largely to preserve existing power relations, the renewable energy political economy may replicate existing dynamics of power, continuing to strengthen the powerful and weaken the marginalised. Energy democracy sees renewable energy transitions as unavoidably political processes as well as key opportunities for advancing renewable energy and democracy together. This framing rejects the view of energy transition as simple technological substitution; rather renewable energy transitions cannot avoid the re-ordering of social and political relations. Energy democracy urges us to consider how, by whom and for whom renewable energy transitions proceed. In this way, energy democracy stands in sharp opposition to the strategy of "renewable energy by any means necessary" and instead embraces energy as politics by other means.

Winners and Losers in the Energy Transition

Some industries will inevitably decline, and some will grow. Of course, the time scales are difficult to predict. One expects that if the Climate Change effects are slow to appear, then a switch to non-fossil fuels will also be slow and vice versa. The politics of the Energy Transition will therefore be diverse and different countries will have divergent views dependent on their own political imperatives.

The energy transition is driving technological shifts, creating winners and losers across industries. Some technologies are rapidly scaling up, while others face decline or disruption. Most countries will eventually try to decarbonise – including the United States. However, they will also argue for special national advantages, for doing things in their own time and will seek for concessions for their most competitive industries. It is useful to identify countries and industries that are "winner" or "losers" as this will identify the political stance for a particular country. Countries who are leaders in renewables will obviously favour political action to move away from fossil fuels.

1. Renewable Energy Leaders

China – The undisputed leader in solar panel, wind turbine, and battery production. Government policies and substantial investment have positioned China as the dominant force in the green supply chain. European Union – Countries like Germany, Denmark, and Spain are leading in wind and solar power, with strong government backing and ambitious climate targets. The EU Green Deal aims to make Europe carbon-neutral by 2050. The United States – Thanks to the Inflation Reduction Act (IRA), the U.S. is ramping up domestic clean energy production, bringing manufacturing back onshore, and competing with China in battery and EV production. However, there is much current uncertainty about the United States' policy at the time of writing.

2. Resource-Rich Countries Benefiting from New Demand

Australia – A major supplier of lithium, rare earth elements, and green hydrogen. Pivoting from coal exports to clean energy materials. Chile and Argentina are home to massive lithium reserves, crucial for EV batteries. The Democratic Republic of Congo dominates cobalt production, essential for batteries, but faces governance and human rights challenges.

3. Emerging Green Energy Exporters

Morocco is investing heavily in solar and wind, aiming to become a major green hydrogen exporter. Saudi Arabia and UAE are traditionally oil-reliant, but both are investing in renewables and green hydrogen to diversify their economies.

Renewable Energy Losers

Russia is dependent on oil and gas exports which have been the backbone of the economy. The shift to renewables and reduced European dependence on Russian gas threaten long-term revenues. Nigeria and Venezuela have oil-dependent economies with weak diversification strategies and so are, vulnerable to declining global oil demand. Iraq and Kazakhstan are highly reliant on fossil fuel exports, facing economic risks if they don't diversify.

Coal-heavy Countries will struggle to transition. India and South Africa are still heavily dependent on coal for energy. Transitioning is difficult due to economic and social constraints. Poland is the largest coal producer in the EU and is struggling with political resistance to phasing out coal and lignite.

Some countries are vulnerable to Supply Chain Shifts. Germany was once a leader in renewables but is struggling with high energy prices due to a past dependence on Russian gas. It is moving towards domestic solutions but facing industrial competitiveness issues.

Winners and Losers in the Energy Transition: Industries

The energy transition is reshaping industries, creating opportunities for some while threatening others.

Winning industries are:

- **Renewable Energy & Storage companies:** Massive investment and falling costs will make them dominant energy sources.
- **Battery Manufacturers:** The demand for lithium-ion and emerging solid-state batteries is skyrocketing.
- **Hydrogen Production:** Green hydrogen is gaining traction for industrial and transport applications.
- **Electric Mobility & Transportation:** Electric Vehicle (EV) Manufacturing – Automakers shifting to EVs (Tesla, BYD, legacy brands like Ford & VW). Charging Infrastructure operators are expanding, and rail, electric buses, high-speed rail, and urban mobility solutions are growing.
- **Mining & Critical Minerals:** Producers will benefit as Lithium, Cobalt, & Nickel are all essential for battery production, driving demand for mineral-rich nations. Rare Earth Elements (REEs)are crucial for wind turbines, EV motors, and electronics, benefiting mining companies.
- **Grid Modernisation and Smart Energy Smart Grid & Digital Energy Companies:** Driven by the need to improve grid reliability and management, demand response, and decentralised energy networks.

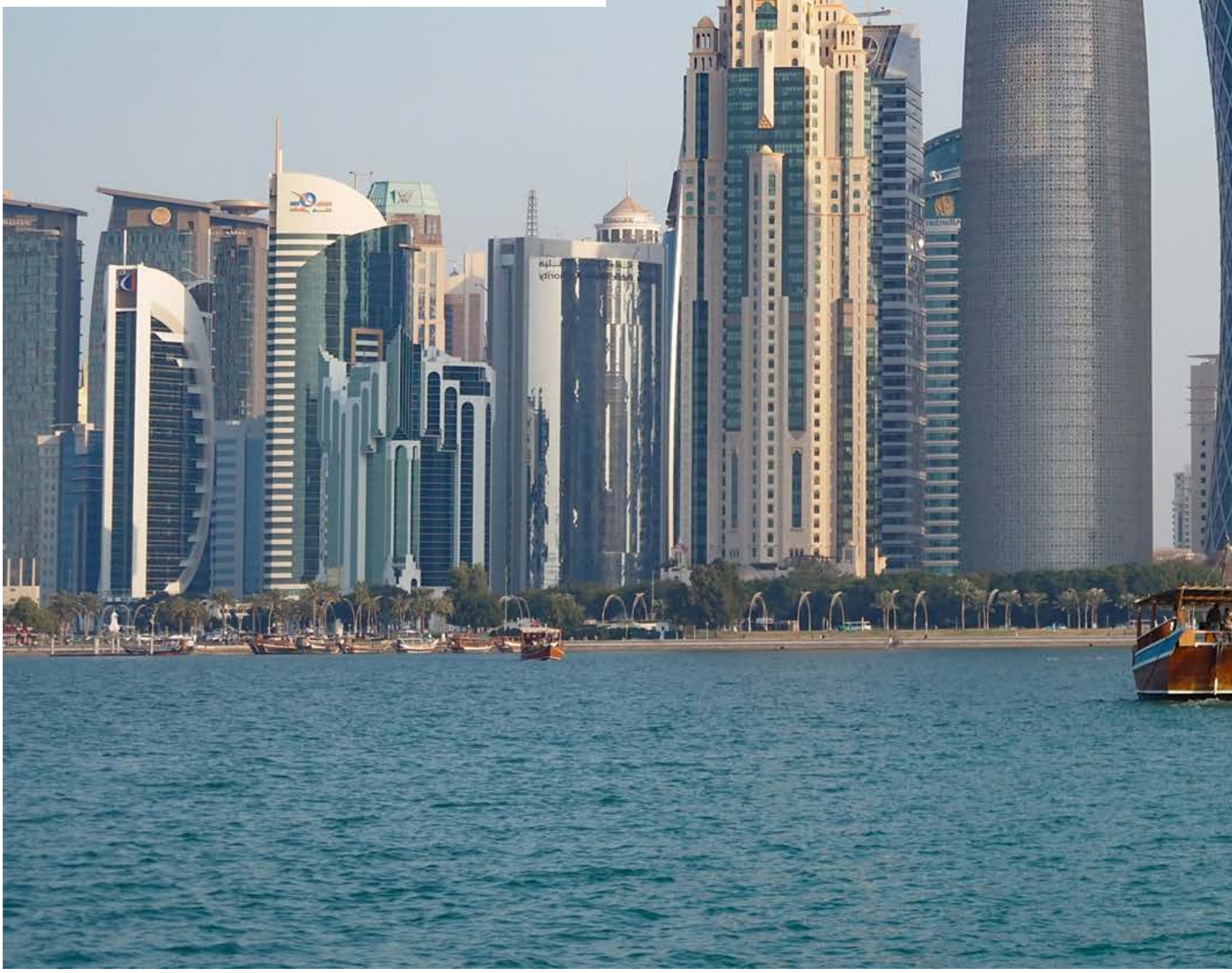
Some industries are facing declines, such as:

- Fossil Fuel Industries, Coal Mining and coal fired power plants are facing closures worldwide due to emissions regulations and cheaper renewables. Oil and Gas Exploration will decline. Whilst demand persists, long-term trends favour cleaner alternatives. The decline in gasoline and diesel use will hurt refineries.
- Internal Combustion Engine. Automakers and their suppliers and distributors focused on ICE Cars where companies have been slow to electrify and risk falling behind.
- Traditional Utilities & High-Emission Industries. Companies reliant on centralised fossil-fuel power plants face pressure to adapt. These are companies such as Steel, Cement and chemicals). Their high carbon footprints make them targets for decarbonisation efforts.

Conclusion

A just, rapid, and effective energy transition requires innovation, inclusive policymaking, collaboration across and within nations, and the active involvement of civil society. It also demands that political leaders confront the entrenched power of fossil fuel interests and reimagine energy systems that are not only sustainable, but also equitable and democratic.

This analysis suggests that the energy transition may lead to a more equitable and just society, because non-fossil fuel sources are geographically more diverse. However, we observe that the sources of enabling minerals, some technologies and means of production are moving in exactly the opposite direction as those levers of the transition are being seized by a few international players.



06

CHAPTER 06

THE ROLE OF NON-FOSSIL FUELS IN POWERING THE FUTURE

The global energy landscape is undergoing a profound transformation as countries pivot away from fossil fuels towards non-fossil energy sources – primarily renewables – to meet future electricity needs. Carbon-free power surpassed 40% of worldwide electricity generation in 2024, a milestone driven by record renewable deployment. Renewable power sources added an unprecedented 858 TWh of generation in 2024 – nearly 50% more than the previous record in 2022. This surge was led by solar energy, which has doubled its output over the last three years to exceed 2,000 TWh annually.

Clean energy transitions are underway, with solar photovoltaic (PV) and wind regularly setting records for growth, helped by policy support, low technology costs and the widespread potential for their deployment. At the same time, nuclear energy is experiencing renewed policy interest as nations seek reliable, carbon-free baseload capacity and new nuclear technologies are being developed (Small Modular Reactors, Generation IV reactors, reactors based on fusion energy). Many countries are now reconsidering nuclear power as a critical component of their energy strategies. This chapter provides a policy-oriented overview of how renewables and nuclear power are expanding globally. It examines current trends, challenges, technological innovations, and projections through 2035 and beyond. ▸

Growing Role of Renewables in Electricity Supply

Renewable energy has seen unprecedented growth in recent years and continued to dominate new power capacity. In 2024, global renewable power capacities increased by 585 GW, a record-breaking annual addition, to reach 4,448 GW in 2024, according to the International Renewable Energy Agency. Most of the expansion came from new solar (+452 GW) and wind capacities (+113 GW), followed by hydropower to a lesser extent (+15 GW). Almost 64% of new global renewable capacity was built in China, which alone added 278 GW of solar capacity last year. A record surge in renewables spearheaded by solar power pushed clean electricity's share to 40.9% of global electricity in 2024, up from 39.4% in 2023. 2024 was the first year that low-carbon sources delivered more than 40% of global electricity (Figure 1).

Over the last decade, the average cost of utility-scale solar PV electricity fell by about 83% and onshore wind costs fell 63%

As mentioned, solar PV led this surge, driven by declining costs, improving efficiency, and strong policy incentives that continue to attract substantial investment. In 2024, solar power generation increased by a record 474 TWh – the largest annual increase ever recorded in absolute terms and the fastest growth rate in six years, at 29%. Solar energy has consistently maintained exceptionally high growth rates, solidifying its role as the primary driver of new electricity generation worldwide. As a result, global solar generation has doubled approximately every three years, reaching 2,131 TWh in 2024 (Figure 2). For the third consecutive year, solar energy posted the largest absolute increase of any electricity source.

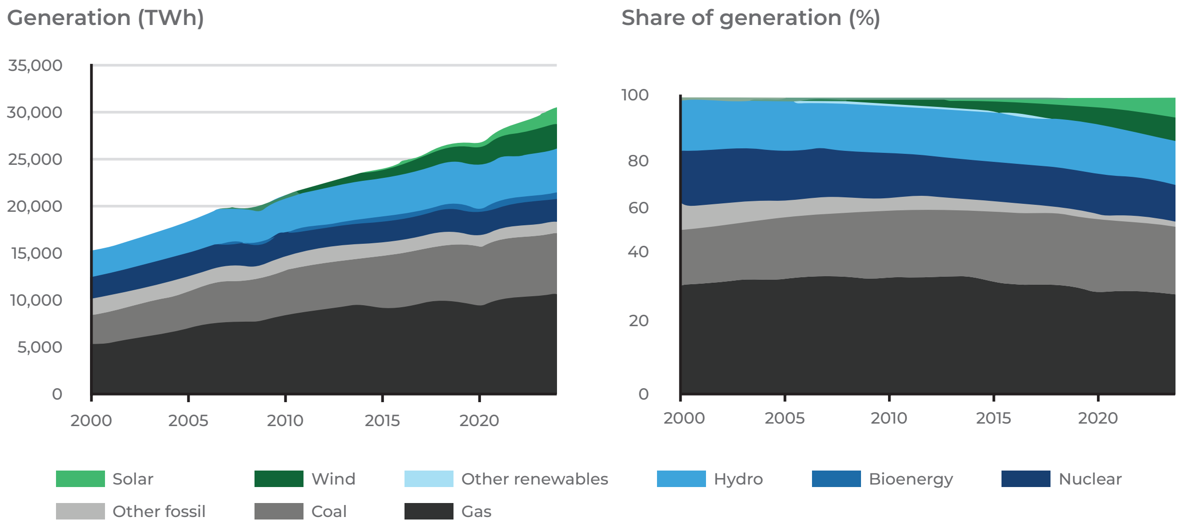


Figure 1: Global Power Generation Evolution, 2000-2024 (TWh) (Source: Ember, Global electricity review 2025)

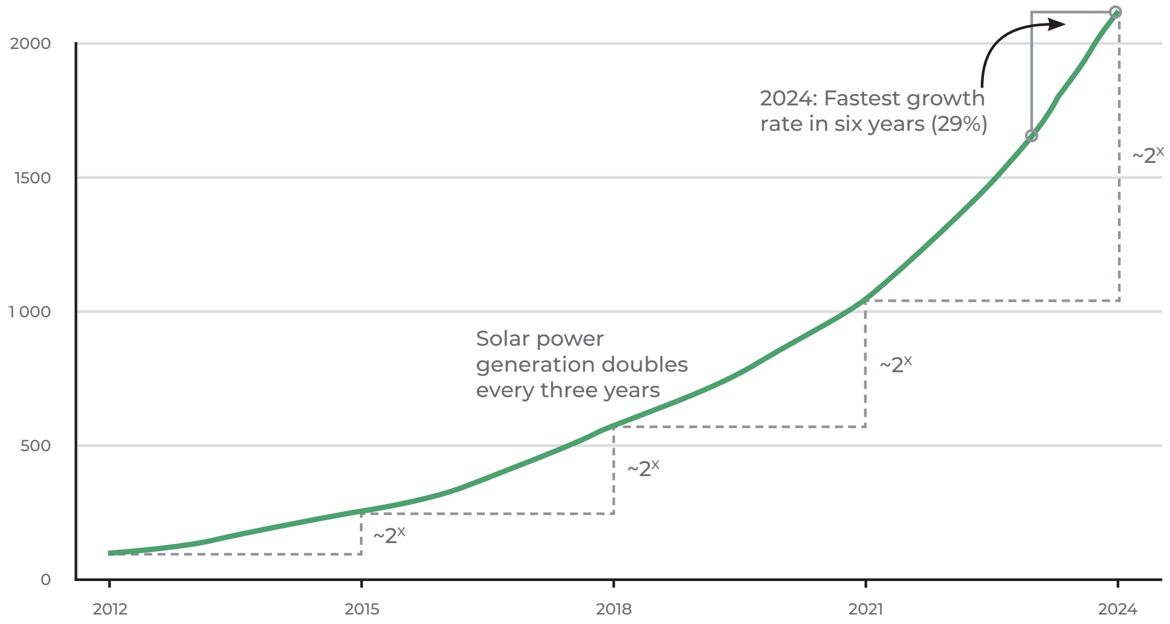


Figure 2: Electricity Generation From Solar, 2012-2024 (TWh) (Source: Ember, Global electricity review 2025)

Economics of Renewables and Technological Development

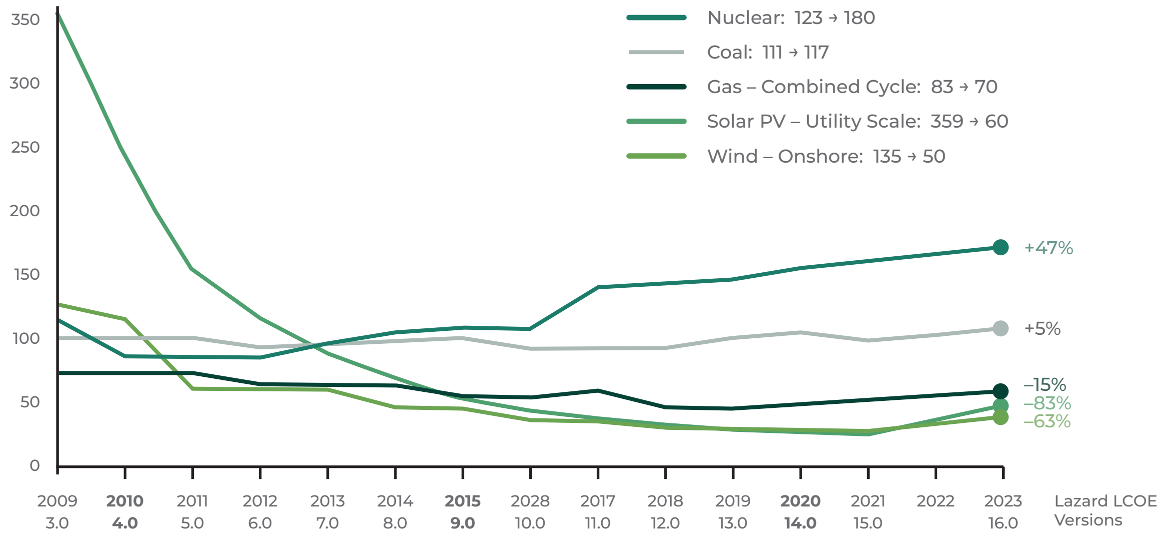
The economics of renewable electricity have improved dramatically, making clean power not only environmentally desirable but also financially attractive. Over the last decade, the average cost of utility-scale solar PV electricity fell by about 83% (2010–2023), and onshore wind costs fell 63% (Figure 3). Thanks to technological innovation and economies of scale, solar and wind projects are now often less expensive than new fossil-fuelled plants – and even competitive with existing ones.

Lazard's latest levelised cost of electricity (LCOE) report finds onshore wind costs around $27–$73 per MWh and utility-scale solar PV $29–$92/MWh. These ranges are well below the costs of new fossil fuel generation: for example, coal-fired power is roughly $69–$169/MWh (nearly double the average cost of solar) and peaking natural gas plants range $110–$228/MWh. Nuclear power remains costly as well, with an average LCOE around $182/MWh for new plants. In short, wind and solar now beat fossil fuels on cost in most regions, even before considering carbon prices or environmental benefits. This cost advantage is a key driver of the rapid uptake of renewables.

In 2024, solar power generation increased by a record 474 TWh – the largest annual increase ever recorded in absolute terms.

Selected Historical Mean Costs by Technology

LCOE values in US$/MWh*



*Reflects total decrease in mean LCOE since Lazard's LCOE VERSION 3.0 in 2009.

Figure 3: The Declining Costs of Renewables vs. Traditional Power Sources (Source: Lazard Estimates, 2023)
Note: This graph reflects the average unsubsidised high and low LCOE range for a given version of LCOE study. It primarily relates to the North American renewable energy landscape but reflects broader/global cost declines.

For example, Saudi Arabia recently achieved a world-record low solar electricity price of around $10.4 per MWh (1.04 ¢/kWh) in an auction, showcasing how inexpensive solar power has become under favourable conditions. Wind power costs have likewise plummeted, especially onshore wind, which in many regions is now one of the cheapest sources of new electricity.

The renewable energy sector is continually innovating, which will ease some challenges and open new applications. Energy storage is a critical focus: advances in battery technology (lithium-ion and emerging chemistries like sodium-ion and solid-state batteries) and falling costs of battery storage are enabling more solar and wind to be stored for use at night or during lulls. Particularly, the cost of battery storage has dropped precipitously – lithium-ion battery pack prices fell from about $1,400 per kWh in 2010 to under $140/kWh in 2023 – making batteries a viable solution to buffer renewable intermittency. However, the challenge of the critical rare mineral has to be addressed by further developing the sector of secondary battery and introducing new batteries using less scarce materials.

Utility-scale battery installations are growing rapidly in countries like the United States, Australia, and China. Other storage forms – pumped hydro, thermal storage, even green hydrogen production – are being pursued to provide seasonal or long-duration storage. Hydrogen is particularly noteworthy: surplus renewable power can be used to electrolyse water, producing hydrogen as a fuel for industry or backup power. While currently a small factor, many countries see "power-to-X" (hydrogen, e-fuels) as a way to absorb very high renewable output in the future and decarbonise sectors beyond electricity.

Solar PV technology continues to improve. New cell materials and designs (such as perovskite solar cells and tandem cells) promise higher efficiency panels. Manufacturing innovations (like larger silicon wafers and AI-optimised production) are cutting PV costs further. In wind, turbines are growing ever larger and more efficient – offshore wind turbines now exceed 15 MW per unit, capturing more energy with each installation. Floating offshore wind platforms are another innovation, allowing turbines to be deployed in deeper waters, vastly expanding the available windy sites. Advanced wind farm designs (using better aerodynamics and smart controls to reduce wake losses) are boosting output.

Another important area is digitalisation and smart grids: using AI and IoT sensors to better forecast renewable output and manage demand in real-time. Smart inverters and grid-forming controls for solar/wind plants now enable renewables to provide some grid services (voltage/frequency support) that were once the domain of conventional plants.

Nonetheless, this progress marks only the initial – and relatively more straightforward – phase of the global energy transition. While the rapid deployment of solar and wind technologies has been impressive, the more complex challenges lie ahead. Achieving the objectives of the Paris Agreement and other climate commitments will require tackling systemic issues such as the integration of variable renewable energy into power grids and the development of new supply chains for emerging technologies, including low-carbon hydrogen and long-duration energy storage. These challenges are particularly acute in developing and emerging economies, where infrastructure limitations, financial constraints, and insufficient technical capacity hinder the large-scale deployment and effective implementation of advanced energy solutions.

Policy Support and Mechanisms

Robust policy support is critical in driving the renewables boom in the power sector. Virtually every major economy has implemented frameworks to promote renewable electricity, from mandates and targets to subsidies and market mechanisms. At COP28, governments pledged to triple renewables capacity, with major economies aiming for at least a 50% increase in renewable capacity or generation by 2030. These targets are embedded in strategic plans and policy documents, including the European Union's (EU) national energy and climate plans, China's 14th Five-Year Plan, India's National Electricity Plan, Japan's 7th Strategic Energy Plan, South Korea's 11th Basic Plan for Power Supply and Demand, and various United States state-level renewable portfolio standards, among others. Some of the key policy frameworks in the EU, United States, China and India and mechanisms are presented below.

The EU has raised its 2030 renewables goal under the European Green Deal and REPowerEU plan. In 2023, the EU adopted a binding target to reach at least 42.5% renewable energy in gross final energy consumption by 2030. This is a big step up from the previous 32% target. Importantly, a 42.5% energy share implies roughly two-thirds of EU electricity from renewables by 2030 (somewhat short of the 69% goal set in REPowerEU).

To achieve this, the EU has implemented a host of policies: competitive auctions for wind and solar (with Contracts-for-Difference or feed-in premiums), streamlined permitting rules, and funds for grid expansion. The EU's electricity market reform in 2023 even proposed requiring countries to assess and plan for flexibility needs (storage, demand response) to integrate high renewables. Individual EU countries have their own targets (e.g. Germany targeting 80% renewable power by 2030, Denmark 100% by 2030, etc.), supported by auctions and feed-in tariff/premium schemes. The EU also operates the world's largest carbon market (ETS), which indirectly favours renewables by increasing fossil generation costs.

In the United States, renewable expansion has been bolstered by federal and state policies, driven by the Inflation Reduction Act (IRA) of 2022. The IRA represents the largest climate and clean energy investment in the country's history – about $369 billion in funding and tax incentives over a decade. It extended and expanded federal investment tax credits and production tax credits for renewable generation. The IRA also incentivises energy storage, transmission, and clean manufacturing, effectively subsidising the entire renewables supply chain. It is recognised that some of the IRA's transition provisions have been scaled back under the present United States administration.

In addition to federal action, state-level Renewable Portfolio Standards (RPS) in 29 states require utilities to supply certain percentages from renewables. Many of which require 50–100% clean electricity by 2040-2050, and federal efforts to accelerate offshore wind leasing (targeting 30 GW offshore wind by 2030). The United States has a national goal of 100% carbon-free electricity by 2035, and while not legally binding, it has guided agencies and utilities to plan for a mostly renewable grid. Overall, a mix of tax incentives, state mandates, and federal spending is propelling U.S. renewables growth at an accelerating rate.

China's renewable expansion is guided by top-down planning and generous support, making it the world leader in installations. The government's 14th Five-Year Plan (2021–2025) includes a target of 33% of electricity from renewables by 2025 and a longer-term goal of non-fossil power (including nuclear) at 50% by 2030. Most notably, President Xi Jinping announced that China will install at least 1,200 GW of wind and solar by 2030, a target that China achieved six years ahead of schedule, reaching 1,206 GW in July 2024.

This remarkable achievement reflects strong policy support: historically, China used feed-in tariffs and generous subsidies to kickstart wind and solar industries in the 2000s–2010s, creating the largest renewable deployment programmes in the world. In recent years, as costs fell, China shifted to competitive auctions and quota mechanisms. For example, new wind and PV projects now often bid for grid connection rights at prices at or below coal benchmarks. There are also renewable consumption obligations for provinces and a green certificate trading scheme to ensure provinces meet their renewable quota. Additionally, China heavily invests in grid infrastructure (e.g. ultra-high-voltage transmission lines) to integrate renewables, and in domestic manufacturing (solar panels, wind turbines, batteries) through measures like low-interest loans and export credits. Moving forward, China has indicated it may raise its 2030 targets further, and its longer-term aim of carbon neutrality by 2060 will necessitate continued growth of renewables well beyond 2030.

India has set ambitious goals to transform its power sector that heavily relies on coal. India's updated target is to have 50% of its installed power capacity from non-fossil fuel sources by2030 (about 500 GW of cumulative non-fossil capacity; within that, the goal is around 450 GW of renewables by 2030). To achieve this, India has implemented a range of support mechanisms. Central to India's approach are reverse auctions for solar and wind projects, which have led to highly competitive tariffs. India's auctioned solar prices (for large-scale, grid-connected solar projects) have fallen to around three US cents/kWh in recent years under these schemes. The government also enforces Renewable Purchase Obligations (RPOs) on distribution companies, mandating that they procure a certain percentage of power from renewables, which creates guaranteed demand. Financial incentives like viability gap funding for solar parks, accelerated depreciation for wind investments, and production-linked incentives for solar manufacturing are also in place. To support the integration of renewables, India has launched programmes such as Green Energy Corridors (building transmission lines for renewables) and is exploring a national electricity market to help share renewable power across states.

Overall, across many countries and regions, policy support takes various forms – renewable targets/mandates, financial incentives (tax credits, feed-in tariffs, subsidies), competitive auctions, R&D funding, grid rules, and more – but the common thread is that all major economies are committed to expanding renewables as a central climate and industrial strategy. Going forward, attention is turning to implementation and integration: streamlining permits, upgrading grids, and ensuring that policy support keeps pace with the rapidly increasing shares of renewables. The next section addresses the challenges of integrating these renewables into power systems and the solutions being pursued.

Renewables' Integration Challenges and Solutions

As renewables take on a larger role in electricity supply, integrating these variable resources into power grids reliably and efficiently is a central challenge. Wind and solar output are intermittent by nature, which means electricity production does not always match demand. This means maintaining the real-time balance of supply and demand becomes more complex. At modest penetration levels, this variability is manageable with existing grid flexibility. But at high shares of renewables, new challenges emerge, such as, ensuring there is enough supply on a windless night, preventing curtailment when there is excess solar at midday, and keeping the grid stable (frequency/voltage control) with fewer traditional synchronous generators online. Moreover, with renewables often decentralised and in remote locations, grid congestion can occur if transmission capacity is insufficient. All these factors pose technical and operational challenges that must be addressed to fully utilise renewables while maintaining a secure electricity supply. In this regard, a range of solutions and strategies is being deployed to tackle the intermittency and integration challenge.

Scale-up of energy storage: Energy storage systems are crucial for buffering the variability of wind and solar. Batteries have seen rapid growth as a flexibility resource – they can charge during periods of surplus solar/wind and discharge when generation dips. Governments and utilities worldwide are investing in large battery projects to provide fast-response balancing power. In 2023, battery storage was the fastest-growing energy technology, with global battery capacity more than doubling (an additional 42 GW installed). Meanwhile, pumped hydro storage (PHS) – the classic form of bulk energy storage – remains vital. Pumped storage hydropower uses cheap off-peak power (often from renewables or nuclear) to pump water uphill, then releases it to generate electricity at peak times. It now stands for over 180 GW worldwide and still provides the majority of grid storage globally. Many grid operators are already using battery and hydro storage to smooth out short-term fluctuations and to provide reserves and frequency regulation. As storage costs continue to fall and deployment rises, it greatly enhances the grid's ability to accommodate high renewable shares.

Demand-side management: Another powerful tool is demand response (DR) which entails managing and shifting electricity demand to better align with renewable supply. Instead of only ramping generation to meet demand, grid operators can also adjust or incentivise changes in consumption. For example, large industrial users or aggregated commercial/residential loads can reduce usage during a supply crunch or increase consumption when there is excess renewable energy. This can be facilitated by dynamic pricing or direct load control programmes. By shifting flexible loads, such as water heating, HVAC cooling, electric vehicle charging, and certain industrial processes, to periods of high renewable energy output, DR can play a crucial role in absorbing surplus solar and wind generation while alleviating peak demand pressures.

Some regions are already leveraging these measures. For instance, Texas has a large industrial DR that helps balance its wind-heavy grid, and countries like Japan and Australia are using smart appliance programmes and battery-enabled DR (via aggregated home batteries/EVs) to shift peaks. Digitalisation and smart grids make demand-side participation easier – smart metres, automation, and IoT devices allow quick response to grid signals. Going forward, more flexible demand (such as millions of electric cars that can charge at optimal times, or smart buildings that adjust HVAC usage) will greatly ease renewable integration by providing a controllable buffer that was not available in traditional grids.

Grid expansion and modernisation: Upgrading the physical grid infrastructure is fundamental to integrating high levels of renewables. Often, the best renewable resources (strong winds, intense sunlight) are located far from population centres. Building new transmission lines is therefore critical to connect renewable-rich areas to load centers and to enable power sharing across regions. Strong interconnections help smooth variability and reduce curtailment by allowing the export of surplus electricity. Many countries have launched major transmission initiatives. For example, China constructed a vast network of ultra-high voltage (UHV) transmission lines, spanning tens of thousands of kilometres, to transport wind and solar power from regions like Xinjiang and Gansu to eastern cities. Germany is building north-south transmission corridors to carry wind power. India's Green Energy Corridors are linking its solar/wind zones to the grid.

Along with new lines, modernising grid management is crucial. This includes deploying advanced technologies – sensors, automation, and AI-driven controls – to better monitor and balance the system in real time. Importantly, grid stability requirements are being updated to accommodate inverter-based resources. Modern wind turbines and solar inverters can now provide services like frequency response and voltage support through sophisticated controls. However, many grids still require updates to codes and operator practices to fully utilise these capabilities.

Additionally, regional power market integration helps – larger balancing areas mean more flexible resources to smooth variability. Examples include the EU's integrated electricity market or efforts in Africa, such as new solar projects within the West African Power Pool framework, enabling renewables trade across borders.

Dispatchable flexible generation and other balancing resources: While the focus is on new technologies, existing dispatchable power plants can continue to play a supporting role in renewable integration. Open cycle gas turbine plants are generally more flexible and can ramp up or down quickly to adjust to the fluctuating supply from renewables like wind and solar. This quick response time makes natural gas a suitable choice for balancing the intermittency of renewable sources. But, this is at the cost of energy efficiency as the Open Cycle Gas Turbine have very low efficiency, unless the heat they release is recovered for some suitable use cases. Additionally, CCS (Carbon Capture and Storage) technologies are expected to gain significant traction, with natural gas-fired plants being retrofitted with CCS starting in the 2030s, contributing to low-emission electricity generation and supporting global climate targets.

Hydropower (with reservoirs) remains a critical balancer in many systems – it can increase or decrease output very rapidly. Countries like Brazil, Norway, and China use hydropower as the battery of the system to counter variable wind and solar. Other zero-carbon flexibility options are in development, such as green hydrogen fuel (excess renewables used to produce hydrogen, which can be burned in turbines or fuel cells for power when needed) and advanced geothermal or biomass plants that can operate on-demand.

In conclusion, while high levels of renewable energy penetration introduce significant operational and planning complexities, a broad suite of solutions is being deployed to safeguard power system reliability. At the heart of these solutions is enhanced system flexibility, enabled by energy storage, demand-side response, flexible generation, robust transmission networks, and advanced control systems. Persistent challenges remain, including extended periods of low renewable output and the need for viable seasonal storage solutions. However, ongoing innovation in areas such as long-duration energy storage, sector coupling (e.g., converting excess electricity into heat or hydrogen), and smart grid technologies offer promising pathways to address these issues.

Hydropower Developments

Hydropower deserves a separate discussion as it holds a unique and longstanding position as the largest single source of renewable electricity. It provides abundant, low-carbon electricity (often as baseload or mid-merit supply) and other essential grid services, such as flexibility and storage. As of 2024, hydropower accounts for over 14% to the global power generation. Many countries continue to depend heavily on large hydro reservoirs to meet their electricity needs. For instance, hydropower accounts for approximately 99% of electricity generation in Paraguay, 90% in Tajikistan, and 89% in Norway. Both, Brazil and Canada generate around 55% of their electricity from hydro resources. A number of African and Asian nations also exhibit high levels of hydropower dependence.

Rising electricity demand continues to sustain strong interest in hydropower projects, with approximately 590 GW of new capacity planned globally, according to the International Hydropower Association. Notably, over 210 GW of this planned capacity consists of pumped storage hydropower (PSH) projects under development, underscoring hydropower's growing role in complementing intermittent wind and solar generation, ensuring grid stability to power systems. Notably, pumped hydro still accounts for over 90% of the world's energy storage and remains critical for multi-hour and seasonal balancing.

Despite its benefits and an impressive pipeline of new projects, hydropower developments have slowed considerably in recent years. From 2015–2020, typically 15–20 GW were added globally each year; in 2021–2023, additions averaged closer to 10–15 GW per year. This slowdown is attributed to a combination of factors. One prominent factor is high upfront costs for construction and installation that often makes it less competitive compared to rapidly advancing solar and wind technologies. Environmental concerns, including the disruption of ecosystems, flooding of land, biodiversity loss, and displacement of communities, have intensified scrutiny and opposition. This results in lengthy and uncertain approval processes. Geopolitical tensions over shared water resources, along with growing public opposition to large-scale dams, can further hinder the growth potential of hydropower.

A significant issue that emerged recently is the impact of climate variability on hydropower. Climate change is altering precipitation patterns, with recurring heatwaves and droughts threatening its reliability and efficiency. The year 2023 was illustrative: severe drought conditions in a few key hydropower countries, including China, India, Canada, the United States and Vietnam, led to subpar hydropower generation. Globally, hydro output in 2023 was down by about 100 TWh (more than 2%) compared to 2022. Climate impact adds uncertainty to future yields, which can deter investment or require adaptation (like redesigning dam spillways for floods). Some countries are exploring retrofits to enable dams to handle more variable inflows or adding turbines to existing non-powered dams as lower-risk projects.

Meanwhile, a notable aspect of hydropower is its dual role in water management and energy. Many countries value hydro not just for electricity but for irrigation, drinking water, and flood control. Climate change is increasing the importance of water storage (for both drought and flood mitigation), and more dams will be needed for water security. So even if energy economics alone wouldn't drive a dam, water needs might – and adding power generation can improve the project's viability. This integrated perspective may spur hydro projects or expansions of existing reservoirs (raising dam heights, etc.).

In terms of policy support, hydro often does not receive direct subsidies as wind or solar because it's older and in most cases handled by state utilities. However, some measures exist. For example, the EU's taxonomy recognises small hydro as green, and multilateral development banks finance hydro in developing countries at concessional rates. Pumped storage projects are increasingly supported by governments (the US DOE has grants for PSH R&D, China subsidises pumped storage construction, etc.) because pure market economics struggle to value their flexibility. There are also bilateral initiatives. For instance, the UK and Norway are collaborating on "green interconnectors" where Norwegian hydro effectively provides backup for UK wind in exchange for power exports.

Despite existing challenges, hydropower remains a cornerstone of many clean energy systems and continues to expand in several regions. Looking ahead, much of this growth is expected to come from the development of

Despite challenges, hydropower remains a cornerstone of clean energy systems, with new growth expected in Asia Pacific, Africa, and Latin America.

hydropower plants, particularly those utilising conventional reservoirs, and PSH projects in the developing economies of Asia Pacific, Africa, and Latin America. These regions combine strong growth in electricity demand with significant untapped hydropower potential, positioning hydropower as a strategic component of their energy transitions.

Particularly, China, besides large-scale projects, aims to add 80 GW of PSH by 2027 within its policy 'Guidance Opinions on Strengthening Grid Peaking Energy Storage and Smart Dispatch Capacity'. Countries in South and Southeast Asia have numerous large-scale hydro projects to meet growing demand and also export power. Africa has huge untapped potential (only about 11% of Africa's hydro potential is utilised) and projects like Grand Ethiopian Renaissance Dam (5.1 GW) will boost Africa's generation. The DRC's proposed Inga dam (40 GW potential) is a long-standing mega-project that could light up much of sub-Saharan Africa if it proceeds. Latin America is more saturated, but the region is projected to add capacity in countries like Brazil, Venezuela, and Paraguay, which continue to harness their vast water resources.

Africa has huge untapped potential—only 11% of its hydro resources are utilised—while projects like the Grand Ethiopian Renaissance Dam (5.1 GW) and the proposed Inga Dam (40 GW) could transform the region's energy landscape.

At the same time, in North America and Europe, a key focus is on upgrades and optimisation of existing hydropower, improving turbine efficiency, adding pumped storage capability to existing reservoirs, and enhancing safety. These upgrades can yield more power without new dams. The United States, through incentives in the 2021 infrastructure law and the IRA, is providing tax credits for hydropower rehabilitation and efficiency improvements. This will help many US hydro plants to extend their life and modestly increase output.

Finally, although currently the growth rate of hydropower has slowed, its global absolute output continues to rise modestly, and it remains indispensable within a renewables-dominated energy system. As climate change increasingly affects water availability and hydrological patterns, hydropower operators will be required to adopt more flexible operational strategies and potentially enhance regional coordination to maintain system reliability.

Hydropower's role is thus evolving from serving as the dominant source of renewable electricity to becoming a foundational element that supports grid stability and storage in a system increasingly reliant on variable renewable energy sources. Its unique attributes – dispatchability, rotational inertia, and large-scale storage capacity – position it as a critical enabler of wind and solar integration. Its long-standing legacy in power generation is set to endure, albeit increasingly in tandem with advancing renewable technologies.

The Resurgence of Nuclear Energy: Opportunities and Challenge

Nuclear energy is experiencing renewed global momentum. After a decade of stagnation following the Fukushima disaster, many countries are reassessing nuclear power as a key option to enhance energy security and achieve climate targets. Its ability to provide reliable, carbon-free electricity has re-positioned it in the evolving energy landscape.

Rising Global Support and Deployment for Nuclear

Policy support for nuclear energy is growing. In December 2023, over 20 countries pledged to triple global nuclear capacity by 2050. Traditional nuclear energy users—such as Japan, South Korea, France, and the United States—are extending reactor lifespans and reversing phase-out plans. Simultaneously, countries like China, India, Russia, Iran, the UK, and several EU member states are supporting new nuclear builds. Emerging economies including Egypt, Bangladesh, Saudi Arabia, Türkiye, and Poland are planning to introduce nuclear power.

Small Modular Reactors (SMRs), Generation IV reactors, reactors based on fusion energy are gaining traction due to shorter construction times, greater flexibility, and modular deployment. Though SMRs are essentially scaled versions of existing nuclear technologies—some of which have been used for decades in naval applications—their commercial deployment is only just beginning. As of 2025, a few SMRs are under construction, with several designs under regulatory review or testing.

Another promising application is the production of "yellow hydrogen" using nuclear-powered electrolysis. Furthermore, nuclear is increasingly considered for meeting the energy demands of AI and hyperscale data centres. Several data centre developers are exploring direct power procurement from SMRs or large-scale nuclear plants.

Current Status and Regional Shifts in Nuclear Development

As of 2024, nuclear energy accounts for just 9% of global electricity generation—the lowest share in over 45 years. This decline reflects a lag in new nuclear deployment relative to the rapid rise in electricity demand. Around 440 reactors are operational globally, with a combined capacity of 398 GW. However, much of this capacity is between 30 and 40 years old, posing challenges for long-term energy planning. New additions are being partially offset by permanent shutdowns, especially in North America and Europe.

The Asia-Pacific region has become the new centre of growth. Seventy-nine reactors—equivalent to more than 70 GW—are under construction worldwide, with China leading the expansion. According to the World Nuclear Association, China alone has 32 reactors under construction, totalling 34.2 GW. India has also laid out plans to triple its nuclear capacity, targeting 22.5 GW by 2031 from 7.5 GW in 2023.

Obstacles to Expansion of Nuclear

Despite renewed interest, nuclear energy faces several challenges. Chief among them is economic competitiveness. Large nuclear projects often suffer from cost overruns and delays, especially in liberalised markets. Long construction periods (typically 7–10 years) expose investors to financial risks tied to fluctuating market conditions. Private investment is limited without robust government backing.

Additionally, high capital costs and long lead times make nuclear less competitive compared to renewables and natural gas. Safety regulations, tightened after Fukushima, can cause licensing delays and regulatory uncertainty, further complicating project timelines.

Unresolved issues around nuclear waste disposal and decommissioning of aging plants add complexity and costs. Public opposition remains a critical barrier. Negative perceptions, particularly following nuclear incidents, can derail projects. For nuclear energy to regain public trust, the industry must demonstrate next-generation safety standards and secure long-term waste solutions.

New Approaches and Innovations

Financing remains a persistent hurdle. Traditional nuclear projects require either direct state funding or innovative financial structures like Regulated Asset Base (RAB) models or consortium-backed investments. SMRs aim to improve cost-effectiveness through modular, factory-based construction and smaller unit sizes (50–300 MW). These offer lower upfront costs and faster deployment.

In May 2025, NuScale became the first US SMR design to receive regulatory approval for its 77 MW module. In the UK, the Great British Nuclear initiative shortlisted SMR designs from GE Hitachi, Rolls-Royce, Holtec, and Westinghouse, with Rolls-Royce selected for further development. Similar programmes are underway in Canada, France, South Korea, and Japan. However, commercial-scale deployment of SMRs is unlikely before the mid-2030s.

Future Prospects for Nuclear

Nuclear's future hinges on resolving its economic, regulatory, and social barriers. Countries pursuing nuclear expansion are implementing supportive measures—streamlined regulation, financing support, and public engagement programmes. For example, the UK employs both Contracts for Difference (CfD) and RAB funding mechanisms. Japan is extending plant lifespans from 40 to 60 years while planning new builds. The US is considering operating license extensions for some plants up to 80 years.

Geothermal Energy: A Rising Pillar in Clean Power

Global geothermal capacity is steadily growing, rising from 15 GW in 2023 to 16.9 GW by the end of 2024. Next-generation geothermal technologies, such as Enhanced Geothermal Systems (EGS) and superhot rock drilling, are accelerating this trend. These innovations stimulate permeability in hot, dry rock formations through hydraulic fracturing, targeting temperatures above 400°C to unlock dense energy reserves.

Geothermal could supply 15% of global electricity growth by 2050, up from less than 1% today. In the U.S., EGS alone has the potential to increase geothermal output twentyfold—enough to power 65 million homes. California aims to raise its geothermal share from ~4 GW to 40 GW by 2045. Federal funding includes $60 million for pilot EGS and superhot rock projects.

Private sector innovation is key. Quaise Energy is developing deep drilling technology using millimetre-wave beams to melt rock up to 12 miles deep. Fervo Energy, supported by Bill Gates, is advancing horizontal-well EGS. Its Utah-based Cape Station will provide 320 MW to Southern California Edison by 2026, with expansion plans to 800 MW. Meta and XGS Energy are also building a 150 MW facility in New Mexico.

Globally, projects are advancing in New Zealand (174 MW Tauhara), Kenya (Menengai II & III, 35 MW each), Ethiopia (Tulu Moye, 150 MW planned), and Taiwan (1 MW pilot).

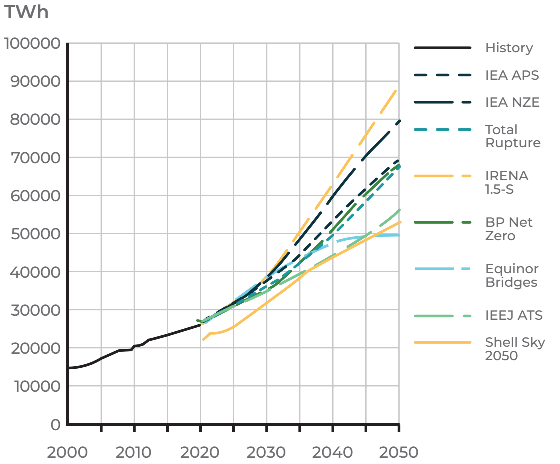
Geothermal's Levelised Cost of Electricity (LCOE) is competitive. Fervo's Cape Station expects an LCOE of $79/MWh, with future costs projected to fall to $50/MWh by 2035—on par with solar + storage and nuclear.

While traditional geothermal is geographically constrained, EGS expands potential nearly anywhere. Challenges remain, including local opposition as seen in Hawaiʻi. Still, with policy support and public engagement, geothermal energy is positioned to become a vital element of the global clean energy future.

The Outlook for Global Electricity Generation and the Role of Non-Fossil Fuels

Global electricity generation increased by 2.5% in 2023, a rate similar to the average over the past decade. This growth rate, which substantially outpaces the rise in total global primary energy demand, highlights the shift toward an increasingly electrified energy system worldwide, a major trend shaping the future of ongoing energy transitions. Projections indicate that global power generation is set to double by 2050, relative to 2023 levels (Figure 4, right graph). At the same time, average electricity generation growth among Net Zero Scenarios

Electricity Generation: Across Alternative and Climate Scenarios



Electricity Generation: Reference Cases and Evolving Policies

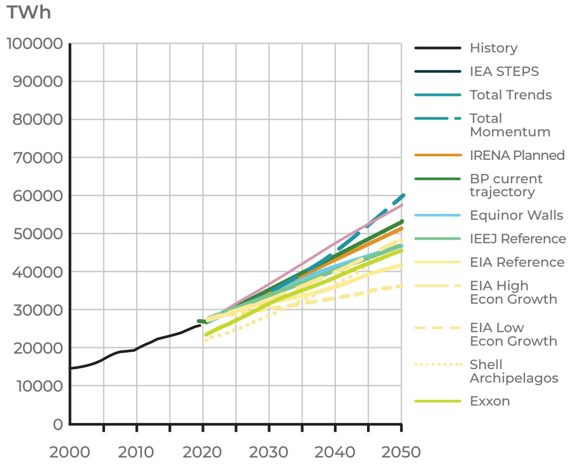


Figure 4: Global Electricity Generation Forecast to 2050 Across Scenarios (TWh). (Source: IEF outlook comparison report, 2025).

Note: IEA WEO 2024, IRENA World Energy Transition Outlook 2024, Equinor Energy Perspectives 2024, IEEJ Outlook 2024, EIA IEO 2023, Shell Energy Security Scenarios 2023, Total Energy Outlook 2024, BP Energy Outlook 2024, and ExxonMobil Global Outlook 2024.

is approximately 15,000 TWh higher than reference cases' trajectories.

This is driven by rising populations, higher living standards, growing prosperity, an expanding service sector and higher industrial output. Better access to energy in some regions, specifically in Sub-Saharan Africa, further contributes to this trend. Accordingly, the share of electricity in total final energy consumption globally is projected to surge. Ambitious climate scenarios project a significant increase in electricity's share, reaching more than 50% by 2050, while reference scenarios expect this rise from 20% to around 30%. This is underpinned by the increasing reliance on electricity to power industrial activities, residential needs, growing EV fleet and advanced technologies, including growing power demand for data centers and AI applications.

Alongside this explosive growth, the power generation landscape is set for a dramatic transformation as the shift toward low-carbon energy sources accelerates. Coal, which currently dominates global electricity generation, is poised for the steepest decline over the long-term. Some Asian countries, especially China and India, have announced the construction of new coal-fired power plants that rely on their domestic coal supplies. However, it is important to recognise that this renewed interest in coal is expected to be short-lived as the global commitment to climate goals remains unwavering.

Gas-fired power generation is set to maintain its current share of 22% over this decade but decreasing thereafter in a range of scenarios. Meanwhile, natural gas can play a crucial role as a reliable and flexible energy source, particularly in complementing the increasing share of intermittent renewables in power systems.

Hydropower is expected to experience annual fluctuations due to varying precipitation and air temperatures, but the overall trend points toward gradual growth. Similarly, nuclear power is projected to increase steadily, driven by policy support and new constructions. However, while both hydropower and nuclear energy are anticipated to see gains in absolute output, their shares in the global power generation mix are projected to decline.

Renewables, led by solar PV and wind, are set to play a much larger role over the next decade and beyond, with their share soaring from 16% in 2023 to around 42% on average by 2035 (Figure 5). Key markets such as China, India, the EU, and the US are spearheading this rapid expansion through aggressive renewable energy policies. At the same time, integrating solar and wind at this scale requires significant grid mod-

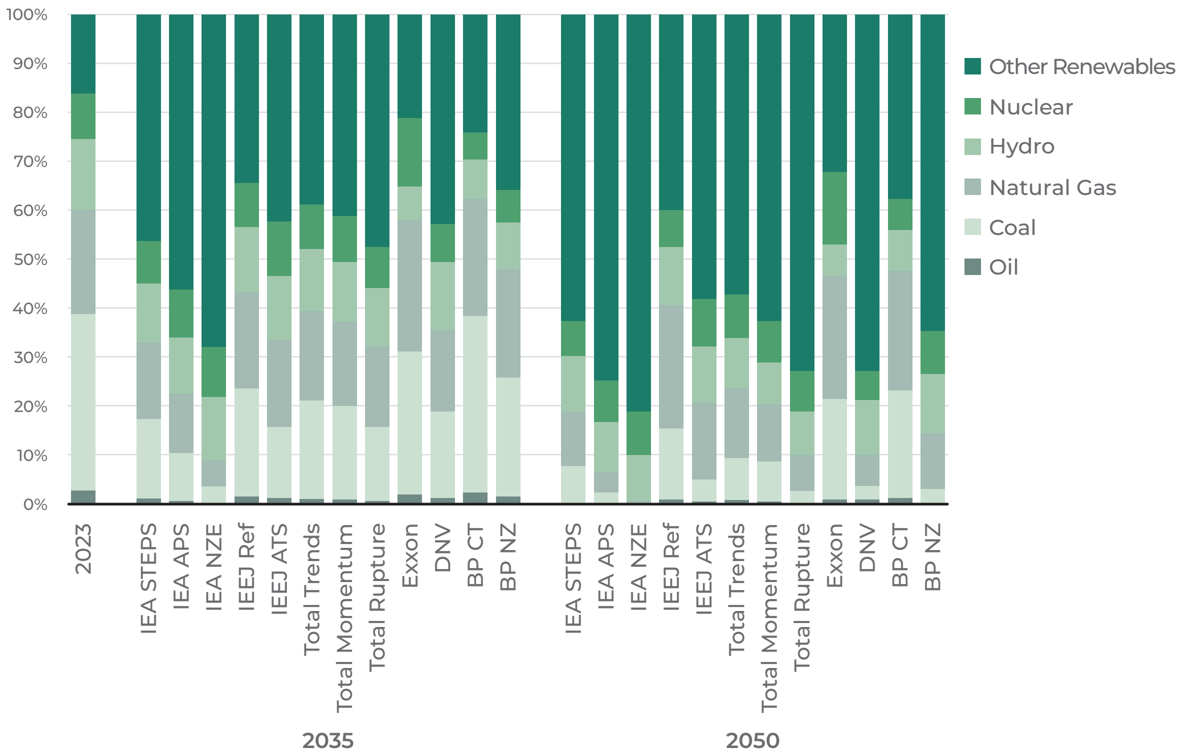


Figure 5: Global Electricity Generation Forecast by Fuel Shares (%) (Source: IEF outlook comparison report, 2025 Note: IEA WEO 2024, IEEJ Outlook 2024, Total Energy Outlook 2024, DNV's Energy Transition Outlook 2024, ExxonMobil Global Outlook 2024, and BP Energy Outlook 2024.

ernisation and enhanced power system flexibility, including through the development of backup generation and energy storage technologies.

Looking to 2050, longer-term scenario analyses show renewables becoming the dominant source of electricity globally. In many pathways consistent with the Paris Agreement, renewables (mostly wind and solar) supply 50–80% of global electricity by mid-century, with most of the remainder from nuclear, hydropower, and a small fraction of fossil with carbon capture.

Reference and evolving policy scenarios project that fossil fuels will still account for over 40% of electricity generation by 2050. Implying that without much stronger policies, renewables growth might mainly add to new supply rather than displace fossil-fuel generation. This viewpoint underscores the importance of accelerating policies to bend the curve.

Conclusion

The chapter illustrates the accelerating global pivot toward non-fossil fuels in power generation, with renewables—particularly solar and wind—emerging as the primary drivers of this transformation. Declining technology costs, coupled with ambitious policy frameworks and rising climate ambitions, have propelled record-breaking capacity additions in recent years, making carbon-free electricity a cornerstone of future energy systems. Solar PV has demonstrated exponential growth due to its scalability and cost-effectiveness, while wind power continues to expand, both onshore and offshore. This trend marks a fundamental restructuring of the global electricity mix, with renewables projected to dominate capacity growth and drive deep decarbonisation across the power sector in the coming decades.

However, the rise of variable renewables introduces new complexities that demand equally transformative changes in power system design and operation. The chapter underscores the critical importance of enhancing system flexibility to maintain reliability amid the intermittency of wind and solar. Energy storage – both short-duration and long-duration – has emerged as a cornerstone of grid resilience, while dispatchable flexible generation, demand-side management, grid digitalisation, and expanded transmission infrastructure are increasingly integral to balancing supply and demand. These technical and institutional innovations are not only essential to enable high shares of renewables but also reflect a broader evolution in how modern power systems are planned and governed.

Complementing the rise of solar and wind, hydropower and nuclear energy continue to play strategic roles within a diversified low-carbon electricity mix. Hydropower remains indispensable for its dispatchable and storage capabilities, despite slower growth and mounting climate-related constraints. Meanwhile, nuclear energy is experiencing renewed policy momentum, driven by its potential to provide stable, carbon-free baseload power and support emerging needs such as hydrogen production and data centre demand. Yet, challenges of cost, public acceptance, and regulatory complexity persist. The future power landscape will thus be shaped by an interplay of rapid renewable deployment, enabling technologies for integration, and the sustained but evolving roles of gas-fired power generation, hydropower and nuclear in ensuring reliability, security, and climate alignment.

While nuclear energy is regaining prominence as a decarbonisation tool, its success depends on strategic policy, innovative technology, and public trust. The years ahead will determine whether nuclear energy can evolve to meet the demands of a fast-changing global energy system.

07

CHAPTER 07

THE ROLE OF HYDROGEN AND CARBON CAPTURE IN THE ENERGY TRANSITION

The global energy transition demands an unprecedented transformation of energy systems to achieve three simultaneous goals: decarbonising economies, strengthening energy security, and supporting continued economic growth. While renewables and energy efficiency remain central to this effort, reaching net-zero emissions will also require deploying a broader set of low-carbon technologies. In particular, hydrogen and carbon capture, utilisation and storage (CCS/CCUS) has emerged as an essential, complementary solution for decarbonising sectors where direct electrification is either limited or impractical.

Hydrogen, when produced through low-emission pathways, such as electrolysis powered by renewables (green hydrogen) or from natural gas with CCS (blue hydrogen), is a versatile energy carrier with applications across multiple sectors. It offers a versatile and scalable energy vector in sectors such as shipping, long-distance transport, steel production, and high-temperature industrial processes, while serving a flexible complement to electricity infrastructure, enabling energy storage. At the same time, CCS provides a pathway to decarbonise fossil fuel infrastructure, to mitigate process emissions and to enable the production of blue hydrogen. Together, these technologies expand the frontier of what is technically possible in deep decarbonisation.

Despite decades of intermittent progress, both technologies are experiencing a resurgence in interest, underpinned by new policy commitments, cost reductions, and growing recognition of their strategic role in long-term climate scenarios. These technologies are increasingly aligned with national net-zero roadmaps, sectoral decarbonisation plans, and industrial competitiveness strategies.

This chapter explores the evolving role of hydrogen and CCS in the global energy transition. It provides a critical analysis of their technological status, market and policy trends, sectoral applications, infrastructure and challenges, and outlook under various decarbonisation scenarios. By examining their synergies and limitations, the chapter aims to offer a realistic and forward-looking view of how hydrogen and CCS can complement other clean energy solutions and contribute to a more sustainable, resilient, and inclusive energy future. ▸

The Promise and Limitations of Hydrogen as a Clean Fuel

Hydrogen could be key in the decarbonisation of hard-to-abate sectors such as industry, transport, and energy storage. Although current production is carbon-intensive, global demand reached 97 Mt in 2023 and over 50 countries have adopted hydrogen strategies — aiming to scale green and blue hydrogen and broaden applications beyond refining and ammonia to steel, transport, and power.

Hydrogen Colour Classification and Production Pathways

Hydrogen production is categorised by colour codes (Figure 1) based on energy sources and environmental impact. Grey hydrogen, primarily produced via steam methane reforming (SMR) of natural gas or coal gasification, dominates current supply but emits significant CO_2—about 9–10 kg per kg of hydrogen for SMR, and roughly double for coal.

Low-carbon hydrogen includes:

- **Blue hydrogen:** Made from fossil fuels with carbon capture (CCUS), reduces emissions by 60–85%, depending on CO_2 capture efficiency and methane leakage control.
- **Green hydrogen:** Created by water electrolysis powered by renewable electricity, emits no CO_2 at production and is seen as key to decarbonisation. However, it's energy-intensive (50–55 kWh per kg H_2) and currently more expensive than other types.

Emerging methods include turquoise hydrogen from methane pyrolysis, yielding solid carbon instead of CO_2, and pink/yellow hydrogen, produced via electrolysis using nuclear or mixed grid power. These approaches offer potential but face technical, cost, and scalability challenges.

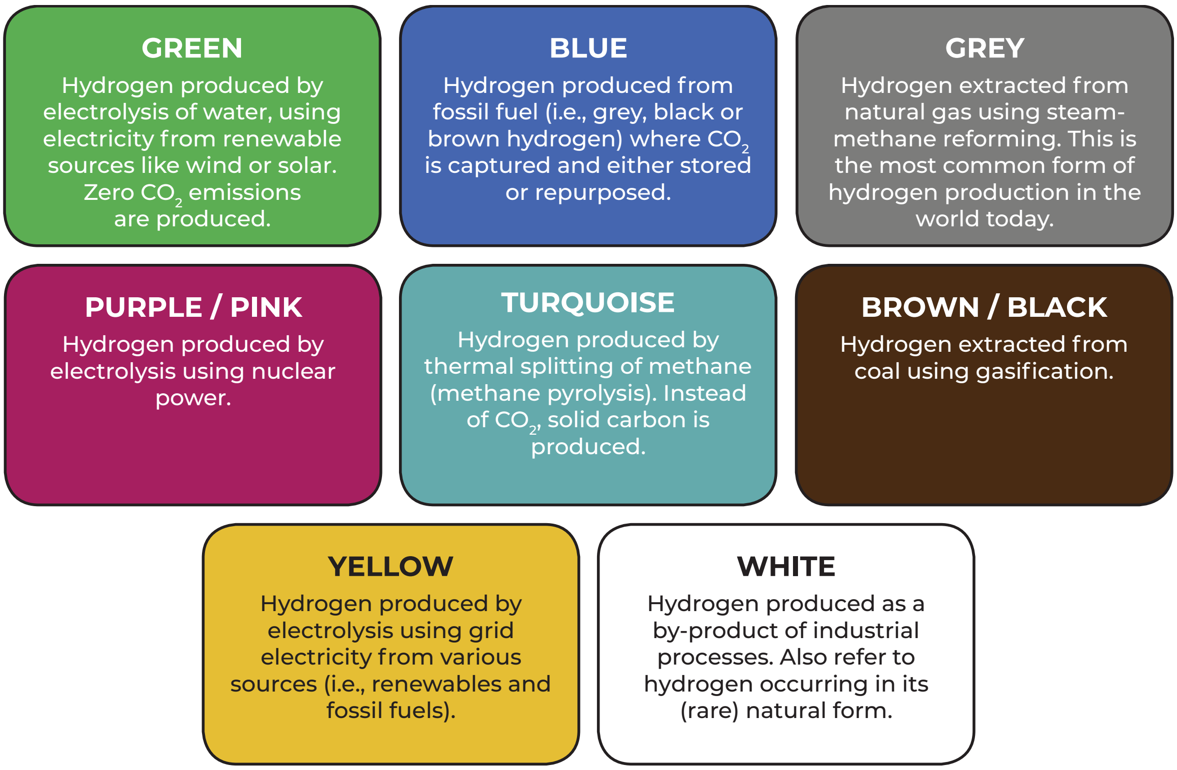


Figure 1: Hydrogen Colour Codes (Source: Applied Economics Clinic —The "Colours" of Hydrogen — Applied Economics Clinic)

Hydrogen Production

Currently, China leads in hydrogen production, accounting for almost 30% of the global total. It is followed by the United States and Middle East with 14% each, and India with 9% (Figure 2). Natural gas and coal gasification account for most output. By-product hydrogen from refineries adds over 15%. Low-emissions hydrogen is under 1% of global supply, primarily from fossil fuels with carbon capture, while electrolytic hydrogen remains minimal and regionally concentrated.

Meanwhile, plans for a significant scale-up of low-carbon hydrogen production are underway. Based on announced project pipelines, global low-carbon hydrogen output could potentially reach 26 Mt annually in the early 2030s, or even 49 Mt, assuming full implementation of all proposed projects, including those in very early development stages. Europe, Latin America, and the United States collectively account for more than half of this projected capacity, reflecting strong policy support, investment momentum, and emerging hydrogen strategies in these regions.

According to project announcements, Europe is expected to produce between 5 and 8 million tonnes (Mt) of low-carbon hydrogen via electrolysis by 2030. In Australia, electrolytic hydrogen production could reach 1.5 to 6 Mt over the same period, reflecting growing investments in renewable-powered hydrogen projects.

The United States is projected to lead in hydrogen production from fossil fuels with CCUS, with output reaching 5.6 Mt by 2030 (or over 3.5 Mt even when excluding early-stage projects). Europe follows, with anticipated CCUS-based hydrogen production exceeding 3 Mt annually by 2030. In Europe, these CCUS-linked projects are primarily concentrated in the United Kingdom (UK), the Netherlands, and Norway – countries with significant geological potential for CO_2 storage (Figure 3).

Despite a surge in announced projects for low-emissions hydrogen production, progress has been uneven. Over the past year, several initiatives have faced delays in final investment decisions (FIDs) or have been cancelled altogether, reflecting a range of persistent challenges. These include regulatory and demand uncertainties, licensing and permitting constraints, financial barriers, and operational complexities. In this context, realising the full potential of

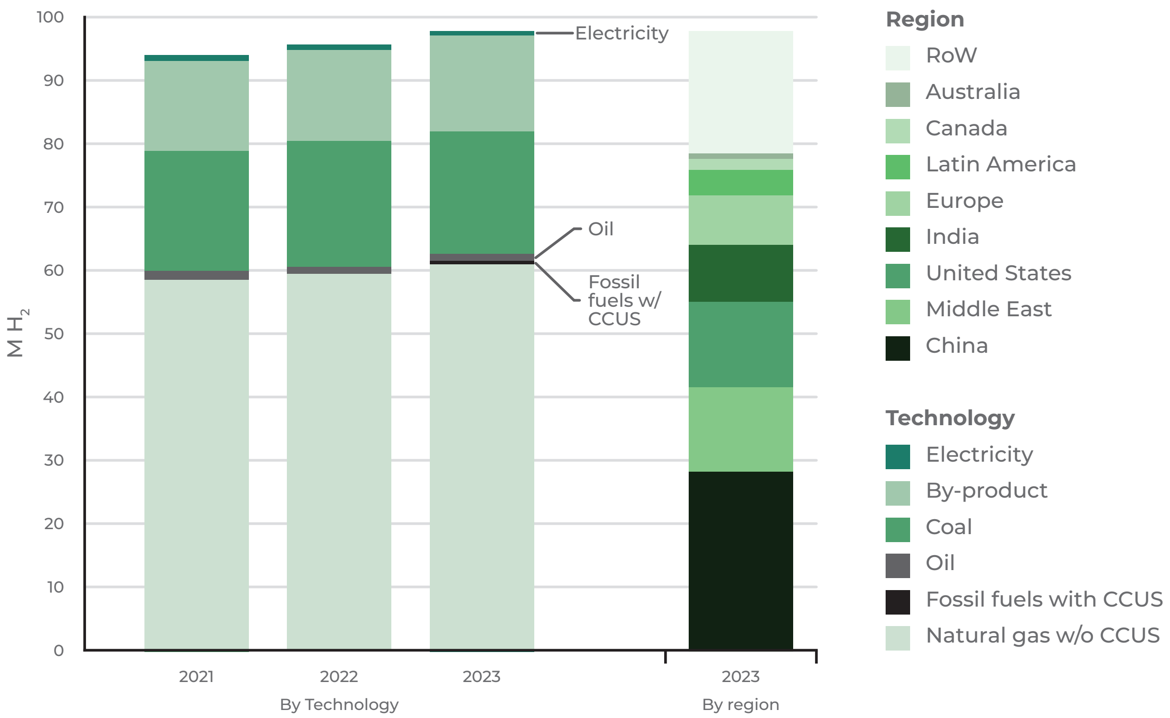


Figure 2: Hydrogen Production by Technology and by Region (Mt H2), 2021-2023 (Source: IEA's Global Hydrogen Report 2024)

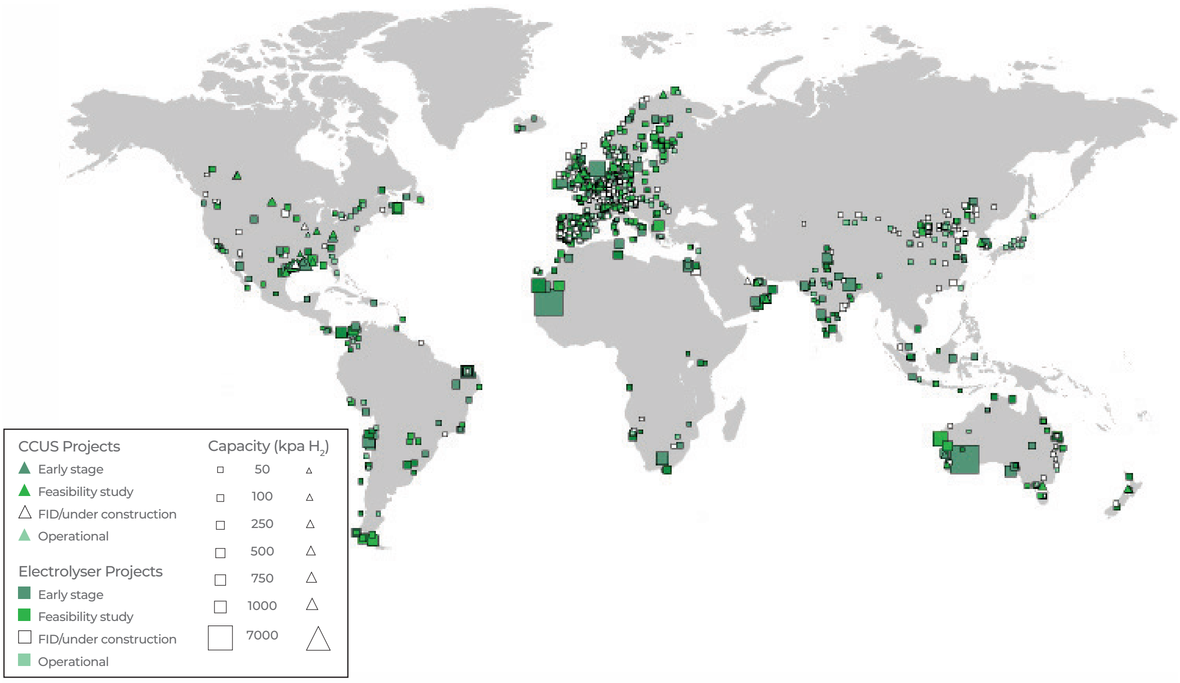


Figure 3: Map of Announced Low-Emissions Hydrogen Production Projects, 2024. (Source: IEA Hydrogen Projects database – October 2024)

low-carbon hydrogen will depend not only on the deployment of mature technologies, but also on the development of supporting infrastructure and the implementation of robust demand-side policies to shift markets away from grey hydrogen.

Hydrogen Demand

The "Hydrogen Economy" concept emerged in the 1970s, coined by electrochemist John O'M. Bockris as a clean energy alternative to fossil fuels. The 1973 oil crisis spurred interest, leading to the first dedicated conference in 1974 and the founding of the International Association for Hydrogen Energy. Initial government support, especially in the United States and Japan, focused on hydrogen R&D. However, stable oil prices and high costs hindered progress through the 1980s–90s, despite foundational research in fuel cells and electrolysis. Hydrogen regained attention in the 2000s amid rising climate concerns. Yet, its use remains concentrated: in 1975, 94% of hydrogen served ammonia production and refining; in 2023, these sectors still accounted for the bulk of demand—about 75 Mt out of 97 Mt total (Figure 4). Emerging uses like power and transport remain limited. Most hydrogen is produced and used locally, with only minor cross-border trade or transport via pipelines or in derivative forms.

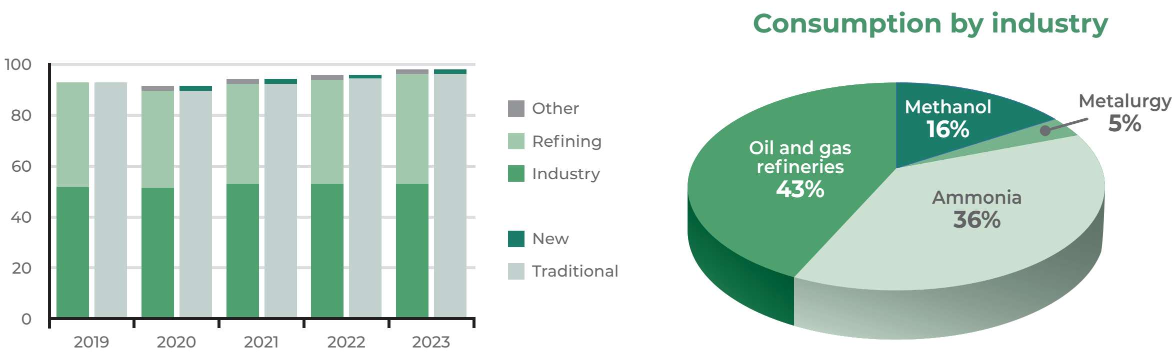


Figure 4: Hydrogen Demand Trend, 2019-2023 (Mt), and Consumption by Sector in 2023 (%) (Source: IEA's Global Hydrogen Report 2024)

Traditional Applications

Refineries are major hydrogen consumers, using around 41 Mt annually, mainly via on-site fossil fuel-based production. North America and China lead in refinery hydrogen use. To decarbonise, refineries are adopting blue hydrogen via carbon capture and blending in green hydrogen. Projects in Europe and North America, including Spain's Cartagena and Germany's Schwedt, demonstrate early green hydrogen integration.

In industry, hydrogen demand reached 53 Mt in 2023, with ammonia production accounting for about 60% of this total. Ammonia, vital for fertilisers, remains carbon-intensive, predominantly using natural gas and coal. Green ammonia from electrolysis is gaining traction, with major projects underway in Norway, the United States, and Brazil.

Methanol production, consuming about 15 Mt of hydrogen, is the second-largest industrial use. Like ammonia, methanol production is CO_2-intensive, with China dominating output through coal-based processes, though interest in cleaner methods is growing

Emerging Applications by Sector

Hydrogen is expanding into industry, transport, buildings, and power, supporting decarbonisation where electrification is difficult, despite limited current adoption.

Industry (Iron and Steel and Other Industrial Processes)

Heavy industries like steel, chemicals, and cement are key targets for hydrogen-based decarbonisation. Steelmaking, traditionally reliant on coal and emitting 1.8 tons CO_2 per ton of steel, can shift to hydrogen-based Direct Reduced Iron (DRI) processes. Sweden's HYBRIT project delivered the first commercial green steel in 2021, with a large DRI plant under construction. Similar hydrogen-steel projects are advancing in Germany, France, Spain, China, Saudi Arabia, and Australia.

In chemicals, decarbonising existing gray hydrogen use in ammonia plants and refineries is a major opportunity. Many are transitioning to green or blue hydrogen, with projects adding electrolysers or CCS to steam methane reformers. Hydrogen is also enabling new chemical pathways like e-methanol—made from hydrogen and CO_2—with pilot plants emerging in Iceland, the Netherlands, and China.

Hydrogen could also provide high-temperature heat in cement, glass, and ceramics. Modified furnaces can burn hydrogen in place of fossil fuels. Trials are underway in German cement kilns and glass production, signalling hydrogen's growing role in reducing industrial CO_2 emissions.

Transportation (Road Transport, Shipping, and Aviation)

Hydrogen offers the greatest promise in transport modes where energy density and fast refuelling are critical—such as heavy-duty trucking, shipping, and aviation. It is less suited for light-duty cars.

Road Transport: Fuel cell electric vehicles (FCEVs) like the Toyota Mirai and Hyundai Nexo offer fast refuelling and long ranges but face stiff competition from battery electric vehicles (EVs) due to infrastructure and cost limitations. By 2023, 90,000 FCEVs were on the road, but limited refuelling stations (~1,000 globally) hinder adoption. Momentum is shifting to heavy-duty transport. China leads in fuel cell trucks and buses, with growing deployment in Europe and the United States. Infrastructure remains a barrier, requiring development along freight corridors. Buses benefit from hydrogen in cold climates or long routes.

Shipping: Hydrogen is unlikely to be used directly due to storage constraints. Instead, hydrogen-derived fuels like methanol and ammonia are emerging. Methanol is commercially viable—e.g., Maersk launched a green methanol-powered ship in 2023. Ammonia is earlier in development, with engines under testing. Both require scaling up low-carbon hydrogen production. Niche uses for hydrogen (e.g., ferries) and fuel cells for auxiliary power are also developing.

Aviation: Hydrogen-based synthetic fuels (e-kerosene) are the near-term focus, with demo plants active and EU blending mandates in place. Airbus is developing hydrogen-powered aircraft for 2035. Challenges include storage, safety, and airport infrastructure. Hydrogen propulsion may suit small commuter aircraft by the 2030s, with larger aircraft delayed until 2040s.

Rail: Hydrogen trains offer clean alternatives where battery electric trains fall short. Trials are underway globally, including Japan and Austria, with impressive ranges (over 2,800 km per refuel). Barriers remain in infrastructure and refuelling complexity, but pilot projects are growing.

In all sectors, hydrogen adoption hinges on supportive policy, infrastructure expansion, and scaling up low-carbon hydrogen supply to make these pathways commercially viable and impactful for decarbonisation.

Buildings

Using hydrogen for building heating and cooking has been debated extensively. The idea is to blend or replace natural gas with hydrogen in gas grids, using existing pipeline infrastructure to deliver low-carbon heat. Hydrogen for building heating and cooking has been trialled in small blends (5–20%) with natural gas in Europe, showing minimal disruption but modest CO_2 reduction. Full conversion to 100% hydrogen is being piloted in parts of the UK and Netherlands, though recent UK policy favours heat pumps. No country has committed to a national hydrogen switch. Japan uniquely uses micro-CHP fuel cells in homes. Overall, hydrogen's role in buildings is expected to remain niche, as electric options are more efficient. Large-scale use is unlikely unless hydrogen becomes abundant, cheap, or politically favoured to preserve gas infrastructure.

Electricity Generation and Energy Storage

Hydrogen currently contributes less than 0.2% to global electricity generation, mostly through mixed gases from industrial processes. It has two key roles in power: as a clean fuel for gas turbines and fuel cells, and for long-duration energy storage to complement intermittent renewables. Japan and South Korea lead efforts, trialling ammonia co-firing in coal plants and converting turbines to hydrogen or ammonia blends. Japan and South Korea also launched subsidies to support hydrogen-based power generation. In the United States, the Intermountain Power Project will start at 30% hydrogen use in 2025, targeting 100% by 2045.

Hydrogen is valued for its potential as dispatchable, clean power, though it remains far from cost-competitive without government support. It is also gaining traction as a storage medium, capable of balancing seasonal electricity supply and demand at terawatt-hour scale—unlike batteries. Projects like DATAZERO and Europe's Hydrogen Bank highlight innovation in storage applications. Large-scale hydrogen storage, such as Utah's salt cavern and Austria's Underground Sun Storage, supports future power deployment.

In summary, hydrogen is best suited for hard-to-electrify sectors and strategic applications—not as a universal energy solution.

Regional Demand Patterns and Plans

Hydrogen demand is regionally concentrated, reflecting the location of refining and fertiliSer industries.

China is the largest hydrogen consumer, accounting for 30% of global demand (28 Mt), mainly for ammonia and refining. It aims to increase demand to 35 Mt by 2030 and 60 Mt by 2050. Strong policy support and rapid electrolysis expansion position China as a future clean hydrogen leader.

Europe consumes around 8 Mt annually and plans to scale to 20 Mt by 2030 (10 Mt produced domestically, 10 Mt imported). Policies like REPowerEU, Hydrogen IPCEIs, and the EU Hydrogen Bank aim to boost investment, but regulatory delays have slowed progress.

The United States(13 Mt, 14% of global use) has ramped up support through the Inflation Reduction Act and "Hydrogen Shot" initiative. With generous tax credits and $8 billion for regional Hydrogen Hubs, the it targets 10 Mt by 2030 and 50 Mt by 2050, with new demand expected in heavy transport and industry.

The Middle East (14 Mt) uses hydrogen for refining and fertilisers and is now positioning as a clean hydrogen exporter. Saudi Arabia, UAE, and Oman are launching giga-scale green and blue hydrogen projects, with NEOM planning 1.2 Mt of green ammonia production by 2026.

Japan and South Korea consume 1–2 Mt each but are leaders in hydrogen strategy. Japan, a pioneer in hydrogen power, targets 3 Mt demand by 2030 and 20 Mt by 2050. South Korea aims for 30% of power generation from hydrogen and ammonia by 2050, focusing on vehicle deployment and hydrogen imports.

Globally, momentum is growing through policy, innovation, and international partnerships. Yet, deployment hinges on cost reductions, infrastructure, and market mechanisms to turn plans into scaled, sustainable hydrogen economies.

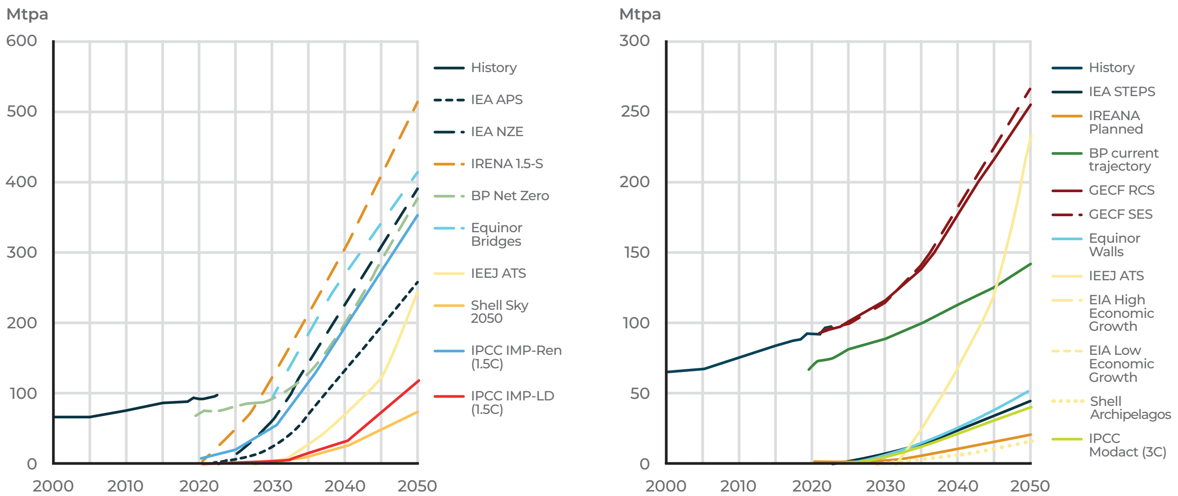
Hydrogen trains are achieving ranges of over 2,800 km per refuel, though infrastructure remains a challenge

Hydrogen Demand Projections: Comparing Global Scenarios

Hydrogen is expected to play an increasingly important role in the decarbonisation of the global energy system, however, projections vary significantly depending on policy ambition, technology cost trajectories, and assumptions regarding sectoral uptake. Scenario-based outlooks from leading organisations highlight both the strategic potential of hydrogen and the uncertainty surrounding its future deployment (Figure 5). Scenarios projections range from about 50 Mt of low carbon hydrogen in 2050 to over 400 Mt in 2050 in the most ambitious climate scenarios. These outlooks anticipate substantial growth in both traditional and emerging applications, with hydrogen evolving into a key energy carrier across multiple sectors.

Hydrogen Demand: Ambitious Climate Scenarios

Hydrogen Demand: Reference Cases and Evolving Policies



Some scenarios only provide an outlook for low-carbon hydrogen, while others include hydrogen made from unabated fossil fuels.

Figure 5: Hydrogen Demand Scenarios Through 2050 (Mt) (Source: IEF outlook comparison report, 2025)

Note: IEA WEO 2024, IRENA World Energy Transition Outlook 2024, Equinor Energy Perspectives 2024, IEEJ Outlook 2024, EIA IEO 2023, Shell Energy Security Scenarios 2023, GECF Global Gas Outlook 2025, BP Energy Outlook 2024, and IPCC AR6.

Hydrogen use is expected to expand in transportation, power generation, and heavy industry, driven by global efforts to achieve net-zero emissions. Emerging applications, such as fuel cell electric vehicles (FCEVs), sustainable aviation fuels (SAF), and hydrogen-based power generation, are projected to gain momentum, supported by policy incentives and technological progress. At the same time, hydrogen will continue to serve as a critical feedstock in established sectors such as chemicals, fertilisers, and oil refining. In these areas, a gradual substitution of grey hydrogen with low-carbon alternatives is anticipated, contributing to industrial decarbonisation goals.

Challenges and barriers for hydrogen growth

Not withstanding the momentum, the hydrogen transition faces significant challenges and barriers that must be addressed to realise its potential. These hurdles are economic, technical, regulatory, and social in nature.

Hydrogen Production Cost

Hydrogen production costs vary by method, scale, and region. Steam methane reforming (grey), blue hydrogen (with carbon capture), and green hydrogen (via electrolysis) differ significantly in price. Grey is cheapest ($0.8–$2/kg), blue ranges from $1.64–$3.09/kg, and green remains costly ($3–$7.5/kg). Green costs may drop 50% by 2030 through cheaper renewable electricity and improved electrolysers, enabling global clean hydrogen adoption.

Clean hydrogen's competitiveness hinges on strong policy support, such as subsidies or carbon pricing, to close cost gaps. Initiatives in the United States and EU aim to make green hydrogen viable. However, high costs for end-use equipment, like fuel cell trucks, pose challenges. Hydrogen must reach $3–5/kg for transport, and $2–3/kg for steel, to compete. Achieving this requires tech innovation, scaling projects, and reducing capital costs, while carbon pricing raises fossil fuel costs, improving hydrogen's relative appeal.

Infrastructure and Logistics Bottlenecks

Building a hydrogen economy demands extensive infrastructure—from production and storage to pipelines, fuelling stations, and end-use systems. Europe's planned 21,000 km Hydrogen Backbone illustrates the scale, with €40–80 billion in costs and major technical, regulatory, and coordination challenges. Converting city gas grids is even more complex, requiring appliance upgrades and public acceptance. Transport

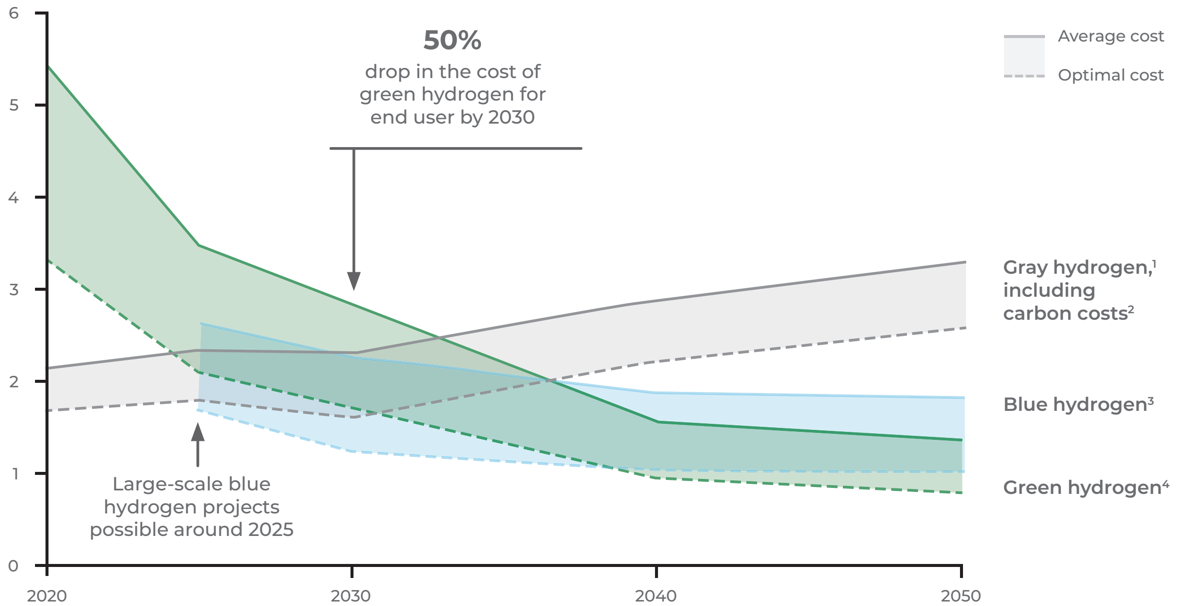


Figure 6: Projected Global Cost of Hydrogen, $ per Kilogram (Source: McKinsey and Company – 2022)

fuelling needs thousands more hydrogen refuelling stations beyond the current 1,000. For global trade via ammonia or liquid hydrogen, few ports are "hydrogen-ready," and developing terminals can take five to ten years due to permitting, safety assessments, and construction demands.

Demand and Market Uncertainty

The same way hydrogen producers face uncertainties about possible offtakers, hydrogen consumers also face uncertainty over availability and pricing, which creates a vicious circle. Securing long-term offtake agreements is key to reducing risk, yet end-users remain hesitant without market stability. Progress is emerging, supported by government tenders, but mutual commitment remains limited. Hydrogen competes with other decarbonisation options like batteries, biofuels, and carbon capture, limiting its demand certainty. Sectoral shifts—like advances in electric trucks or widespread biofuel use—could reduce hydrogen's role. This uncertainty complicates policymaking. Clear, long-term signals such as mandates, low-carbon standards, or carbon pricing are essential to secure investment and ensure a stable hydrogen market.

Environmental and Social Concerns

While hydrogen helps reduce CO_2, it raises environmental and social concerns. Blue hydrogen emits some CO_2 and methane, while hydrogen combustion can still produce NO_x. Electrolysis is energy-intensive, requiring ~50 kWh of electricity per kg of H_2, and competes with other electricity demands. Producing 10 Mt of hydrogen may consume 500 TWh of renewable electricity. Water use is also significant—20–30 litres per kg—especially problematic in arid regions, prompting consideration of desalinated or recycled water. Land requirements for solar/wind installations further complicate deployment.

Safety is another issue; hydrogen is flammable and demands strict handling standards. Public opposition could emerge over perceived risks or land use, making education and regulation vital. However, hydrogen can also create jobs and provide a transition path for oil and gas workers.

Widespread hydrogen use faces high costs, limited infrastructure, and weak demand signals. Strong policies—subsidies, mandates, and public procurement—are

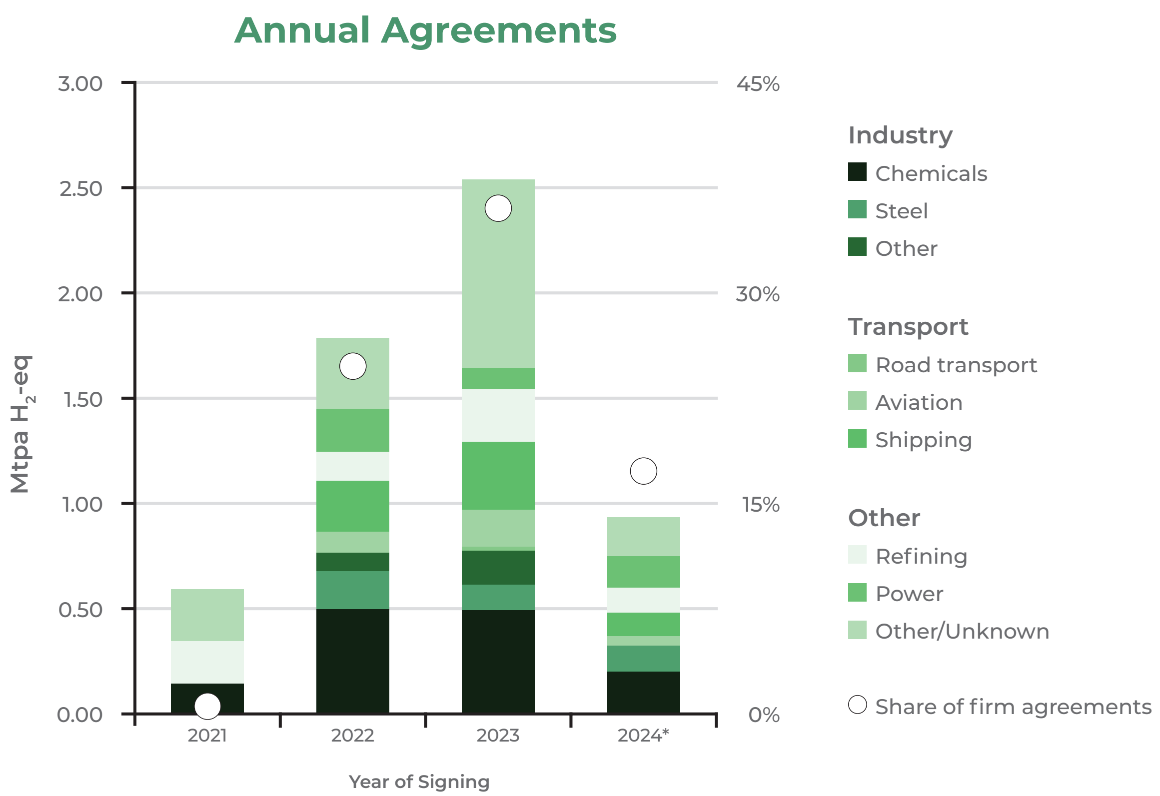


Figure 7: Offtake Agreements Signed for Low-Emissions Hydrogen and Hydrogen-Based Fuels, 2021-2024 (Source: IEA's Global Hydrogen Report 2024)

needed to create a transitional market. Strategic investment in infrastructure, regulatory clarity, and integration with renewable energy expansion will be key. Ensuring sustainability and public support is essential for long-term success.

Carbon Capture, Utilisation and Storage: Scaling a Critical Technology for Net-Zero

Technology Overview and Sectoral Applications

Carbon Capture, Utilisation and Storage (CCUS) is vital for low-emission energy systems. It captures CO_2 from industrial sources using pre-combustion, post-combustion, or oxy-fuel combustion methods—post-combustion being the most mature. Captured CO_2 is then compressed and transported for utilisation or storage. Utilisation includes enhanced oil recovery, chemicals, and synthetic fuels, though most methods only delay emissions. The main climate benefit lies in geological storage, where CO_2 is permanently injected into formations like depleted reservoirs or saline aquifers. Proven industrial practices show such storage can be safe and effective with minimal leakage over long timescales.

Figure 8 provides a visual overview of each step in the CCUS process. While CCUS encompasses both storage and utilisation, this section concentrates mainly on carbon capture and storage (CCS) components, which remain the dominant pathway.

CCS is crucial to many low-carbon strategies as it directly abates CO_2 emissions from ongoing fossil fuel use, especially in sectors where alternatives are limited or expensive. It enables existing power and industrial plants to cut emissions by up to 95%, allowing them to operate with lower emissions. Projects like Canada's Boundary Dam and Texas's Petra Nova have demonstrated CCS feasibility at coal plants, using captured CO_2 for Enhanced Oil Recovery (EOR).

CCS also helps decarbonise hard-to-abate industries such as cement, steel, and chemicals. Norway's Norcem Brevik plant integrates CCS to cut cement emissions by 50%, and the UAE's Al Reyadah captures CO_2 from steel production. In hydrogen production, CCS enables "blue hydrogen" by capturing CO_2 from processes like steam methane reforming. Shell's Quest project and Air Products' Louisiana plant are notable examples.

Bioenergy with CCS (BECCS) is another promising path, offering net-negative emissions. Projects like the Illinois ethanol-CCS facility and the UK's Drax pilot illustrate BECCS applications. Biogenic CO_2 from pulp, paper, or waste-to-energy plants is also a target.

The oil and gas sector remains central to CCS, with natural gas processing accounting for over 60% of current capture capacity. Norway's Sleipner project has securely stored CO_2 since 1996. Countries like Qatar are expanding CCS at LNG facilities to reduce the carbon intensity of gas exports, with Ras Laffan already capturing 2.1 $MtCO_2$/year and aiming for 11 $MtCO_2$ by 2035.

CCS supports climate goals by enabling deep emissions reductions in heavy industry and power, producing low-carbon hydrogen, and achieving negative emissions. While not a standalone solution, CCS complements renewables and efficiency and is critical where alternatives are scarce. Its cost-effectiveness compared to other mitigation

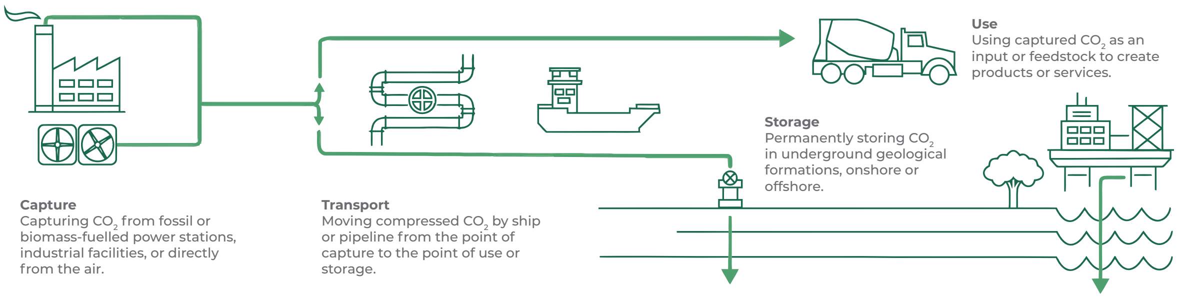


Figure 8: The CCUS Chain (Source: IEA)

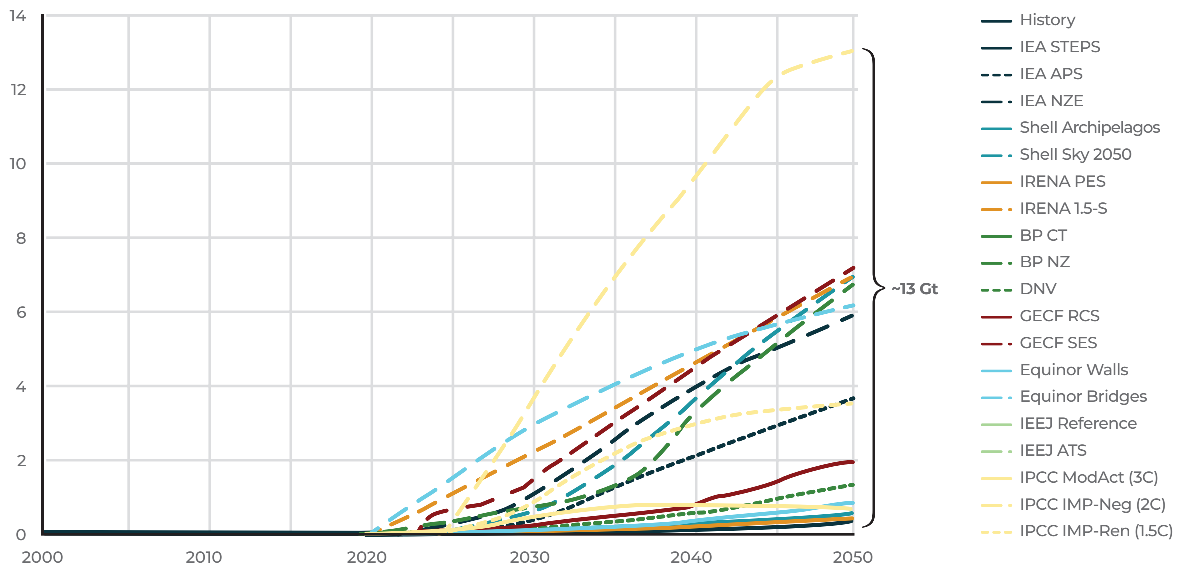


Figure 9: Carbon Capture (CCUS, CCS, BECCS, Industrial) Capacities in Energy Outlooks in 2050 ($GtCO_2$) (Source: IEF outlook comparison report, 2025)

Note: IEA WEO 2024, IRENA World Energy Transition Outlook 2024, Equinor Energy Perspectives 2024, IEEJ Outlook 2024, Shell Energy Security Scenarios 2023, DNV's Energy Transition Outlook 2024, GECF Global Gas Outlook 2025, BP Energy Outlook 2024, and IPCC AR6.

options strengthens its role in climate strategies. To meet climate targets, scaling CCS will require supportive policies, investment in infrastructure, and integration with broader energy systems.

Long-Term Outlook for CCUS to 2050

CCS is central to global net-zero energy projections. Institutions like the IEA, IRENA, BP, and Shell project 4–8 $GtCO_2$ captured annually by 2050 (Figure 9), with the IEA targeting over 1 Gt by 2030. CCS enables both emissions abatement and carbon removals, essential to limiting warming below 2°C. Achieving this requires urgent investment, supportive policies, and infrastructure. Without CCS, climate goals become costlier and harder to meet. Its growing inclusion in scenarios signals that CCS is not optional—it is vital to building a low-carbon, sustainable energy future.

Current Status of Carbon Capture Deployment and Regional Trends

After decades of development, CCS deployment remains at an early-stage relative to the scale required for climate mitigation, but it has gained notable momentum in recent years. As of 2024, there are roughly 50 commercial CCS facilities in operation worldwide, collectively capable of capturing 51 $MtCO_2$ per year. For context, global energy-related CO_2 emissions are on the order of 36,000 Mt per year, so current CCS activity addresses only a tiny fraction of emissions.

However, the project pipeline has expanded rapidly. The Global CCS Institute's latest survey reports a total of 628 CCS projects in various stages (operational, under construction, or in development) as of late 2024 – a 60% increase in the pipeline from the previous year. If all facilities currently under construction are completed and begin operation, the world's operational capture capacity would roughly double to over 100 $MtCO_2$ per year in the next few years. Meanwhile, by 2030, capture capacity can potentially exceed 400 $MtCO_2$ per year based on all current pipeline of projects (Figure 10). The growth reflects that CCS is transitioning from a niche demonstration phase to an emerging industry.

It's also worth noting the diversification of sectors in new projects: whereas the first wave of CCS (2000s–2010s) were often in natural gas processing, many of the upcoming projects target industrial sources (cement,

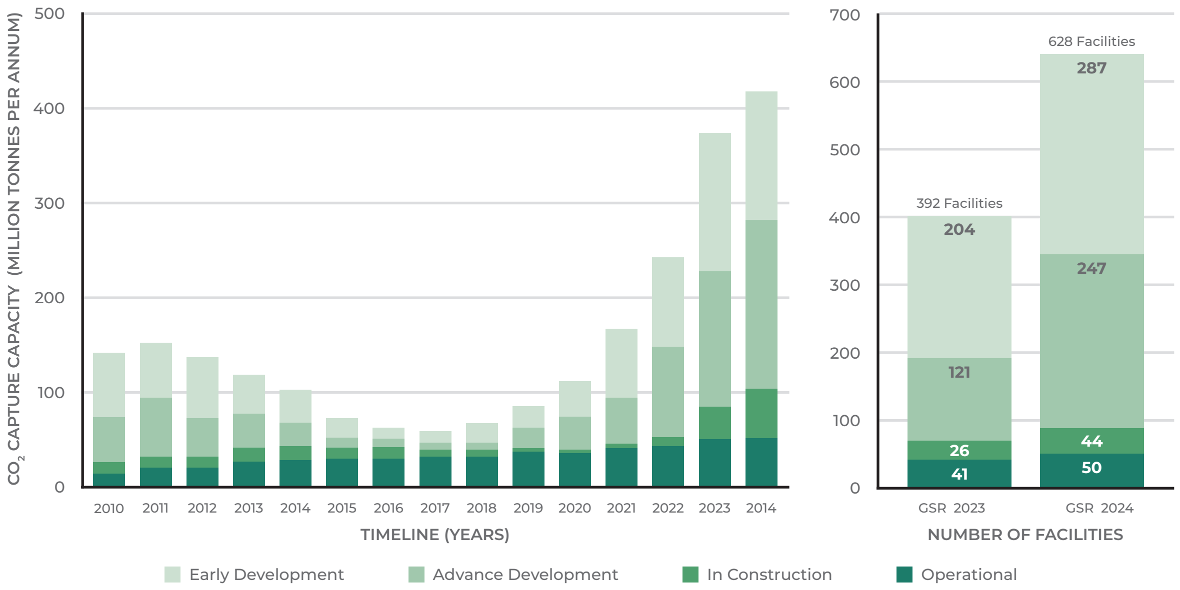


Figure 10: CO_2 Capture Capacity of Commercial CCS Facility Pipeline Since 2010 (Left Graph); Commercial CCS Facilities by Number and Total Capture Capacity in 2023 and 2024 (Right Graph) (Source: Global CCS Institute 2024)

chemicals, ethanol), ammonia and hydrogen production, and power generation. Additionally, the rise of direct air capture (DAC) technologies is noteworthy. These developments reflect the broadening scope of CCS applications, with various industries exploring and investing in this critical technology to achieve their sustainability goals.

Regional Trends

CCS deployment remains geographically uneven, concentrated in regions with favourable geology, policy support, and industrial activity. North America leads globally, with the U.S. hosting 19 of 26 operational facilities. The surge in CCS proposals within the United States stems from enhanced 45Q tax credits ($85–$180/ton), DAC hub funding, and support for industrial CCS under recent legislation. Canada also invests heavily, including in Alberta's CO_2 storage hub and the underutilised Carbon Trunk Line.

Europe, though behind in operational capacity, is undergoing a CCS renaissance with 191 projects in development. It leads in creating CCUS clusters and shared CO_2 transport/storage hubs. Key projects include Norway's Northern Lights (1.5 $MtCO_2$/yr capacity from 2024) and the Netherlands' Porthos (2.5 $MtCO_2$/yr by 2026–27). EU policy plays a major role: the ETS provides strong carbon pricing (€80–€100/ton), while the Innovation Fund and Connecting Europe Facility offer substantial grants for CCS infrastructure.

The 2024 Net-Zero Industry Act sets an EU-wide target of 50 $MtCO_2$ injection capacity by 2030, aiming to catalyse industrial-scale CCS development and meet the EU's 2050 climate goals.

As a special case within Europe, the UK has an ambitious CCUS programme anchored in the development of regional "clusters." The country initially set a target to capture and store 20–30 $MtCO_2$ per year by 2030 through its cluster programme. The clusters were intended to support industry decarbonisation and help the UK meet its 2050 net-zero target.

CCS is gaining importance in the Asia Pacific and Middle East, driven by rising energy demand, fossil fuel reliance, and decarbonisation goals. In China, although CCS remains in early stages, several projects are operational, and the government has integrated CCS into its climate strategies. Notably, China is building the world's largest coal-fired CCS unit (1.5 $MtCO_2$/year) at Taizhou. Projects also target coal-to-liquids, hydrogen, steel, and cement sectors.

Australia is progressing through the Gorgon project and its net-zero roadmap prioritises CCS for LNG and heavy industry. Southeast Asian countries like Indonesia and Malaysia aim to develop CCS hubs, including for importing CO_2 from other nations. Japan and South Korea seek transnational CCS value chains due to limited domestic storage.

Middle Eastern oil producers view CCS as key to decarbonising and maintaining hydrocarbon competitiveness. Saudi Arabia plans a 9 $MtCO_2$/year CCS hub by 2027, scaling to 44 $MtCO_2$/year by 2035. The UAE's ADNOC aims for 10 $MtCO_2$/year by 2030, while Qatar targets over 11 $MtCO_2$/year by 2035, including CCS-integrated blue ammonia via the QAFCO-7 project.

Globally, CCS is moving from demonstration to scaling. Despite limited implementation—especially in power and cement—numerous projects are planned across diverse regions and sectors. Policy support is central to this expansion. Measures such as carbon pricing, subsidies (e.g., 45Q in the U.S.), grants, regulatory frameworks, and national targets are driving project development. Countries with robust CCS policies—like the United States, EU, UK, and Gulf states—are leading this growth. Ongoing, enhanced policy support remains vital to achieving CCS deployment at the scale needed for climate targets.

Challenges of CCUS Scale-Up

Despite the growing support and momentum, CCUS still faces a suite of technical, economic and societal challenges that must be navigated to achieve large-scale deployment. Many of these challenges have contributed to CCS deployment lagging behind past expectations, and they frame the risks and uncertainties that current investors and policymakers are working to overcome.

High Costs and Energy Requirements

CCS is capital- and energy-intensive, raising costs and reducing power plant efficiency by 15–30%. Capture costs range from \$20–\$200/t depending on source type, with transport and storage adding \$10–\$35/t. Without policy support or revenue streams like enhanced oil recovery, most CCS projects face economic viability challenges.

Insufficient Policy and Market Incentives

CCS investment is hindered by weak carbon pricing, policy uncertainty, and unprofitable CO_2 utilisation markets. Without strong incentives or regulations, private investors lack confidence to fund large-scale CCS projects.

Infrastructure and Storage Constraints

CCS requires extensive infrastructure—capture equipment, transport networks, and verified storage sites. Many regions lack pipelines or terminals, and developing them demands coordination, investment, and regulatory approvals. Storage site assessment is complex and slow, and without guaranteed storage access, capture projects face delays, creating a chicken-and-egg deployment challenge.

Technical Risks and Scale-Up Challenges

Scaling CCS faces engineering and cost challenges. Large-scale projects remain limited, often experiencing technical issues and delays. Each industrial site needs tailored solutions, while direct air capture remains costly. Lack of standardised, modular CCS designs hinder efficiency, making widespread deployment slow without advances in mass manufacturing and system integration.

Public Perception and Societal Acceptance

CCS faces social resistance in some regions due to fears of fossil fuel lock-in and CO_2 leakage. Public opposition has delayed or halted projects, especially pipelines and onshore storage. Building trust through simulations with digital twins, CCS clinical trials and transparent communication on safety, monitoring, and climate necessity is vital to secure permits and community support.

Uncertain Long-Term Liability and Regulatory Complexity

CCS faces key challenges including ensuring long-term storage reliability, managing leakage risks, and navigating complex, multi-agency regulatory processes. Project developers may face indefinite liability without insurance or government guarantees, impacting financial planning. Despite previous unmet deployment roadmaps, current momentum is stronger due to urgent net-zero goals and enhanced policy support. However, scaling CCS to meet climate targets requires significant investment, technology cost reductions, and public acceptance. Cross-sector alignment now exists, but success is not guaranteed. If governments and industry deliver on current projects and sustain support, CCS could become central to decarbonisation. Still, CCS is not a standalone solution—it must complement renewables and efficiency. The 2020s will be decisive in determining whether CCS can scale to billions of tonnes annually by 2050.

Conclusion

Hydrogen and CCS are key to achieving deep decarbonisation. Hydrogen, increasingly used beyond chemical feedstocks, shows potential in steelmaking, transport, and aviation. While natural gas-based hydrogen remains cheaper, green hydrogen costs may converge by 2050. Governments are providing subsidies and tax incentives to accelerate deployment. CCS is vital for decarbonising hard-to-abate sectors like cement and steel and is essential for producing blue hydrogen by capturing CO_2 during hydrogen production. Over 50 CCS facilities operate today, with 600+ planned. However, deployment faces challenges: high costs, complex permitting, and policy gaps. Both technologies must scale faster, supported by strong policies and global cooperation. Neither replaces renewables or efficiency, but both are critical enablers in a comprehensive, net-zero strategy.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CHAPTER 08

THE ROLE OF DIGITALISATION AND SMART GRIDS

The 21st-century energy landscape is facing an unprecedented convergence of challenges and opportunities. The global push to limit greenhouse gas emissions, the rise of decentralised power generation, the development of intelligent power equipment and the increasing electrification of transport and industry are all reshaping how energy is produced, distributed, and consumed. At the heart of this transformation lies the need for a smarter, more agile power system, one that can manage complexity, optimise efficiency and enable resilience.

This smarter system is built not through more hardware alone, but through digital intelligence: sensors that perceive grid conditions in real-time, algorithms that predict system needs before they arise, and platforms that enable users to become prosumers, participating in the energy markets rather than passive consumers. This is the promise of energy digitalisation — the foundation of what is now commonly known as the smart grid. ▸

Why Digitalisation Matters

Historically, electric grids were designed for one-way flows of power, from large central plants to end-users. These systems, though effective for decades, were built with analogue controls, fixed assumptions about demand, and minimal feedback mechanisms. But today's world is different. Variable renewable energy, demand-side participation, energy storage, and electric vehicles all require a highly coordinated, data-driven approach to grid operation.

Digitalisation — the application of digital technologies to monitor, control, and enhance the electricity system — transforms this static infrastructure into a responsive, self-optimising network. It enables:

- **Granular visibility** across the grid in real time
- **Predictive maintenance** to reduce failures and costs
- **Dynamic pricing** that reflects actual system conditions
- **Flexible demand management** and consumer empowerment

These are not abstract goals. They are already being realised in cities and nations that are deploying smart metres, intelligent substations, machine learning algorithms, and blockchain-enabled peer-to-peer trading.

The Role of Smart Grids in Energy Transition

In a carbon-constrained world, the energy transition is no longer optional — it is imperative. Renewable energy sources like solar and wind are essential to achieving net-zero goals, but they also introduce volatility and complexity. Smart grids are the infrastructure that makes renewable scalable and dependable.

Furthermore, as energy systems shift toward decentralisation, with homes and businesses becoming producers as well as consumers ("prosumers"), digital coordination becomes critical. Smart grids ensure that these distributed assets — rooftop solar, home batteries, electric vehicles — can be integrated without compromising system stability.

In this way, smart grids are not just enablers of cleaner energy — they are drivers of a more democratic, resilient, and efficient energy paradigm.

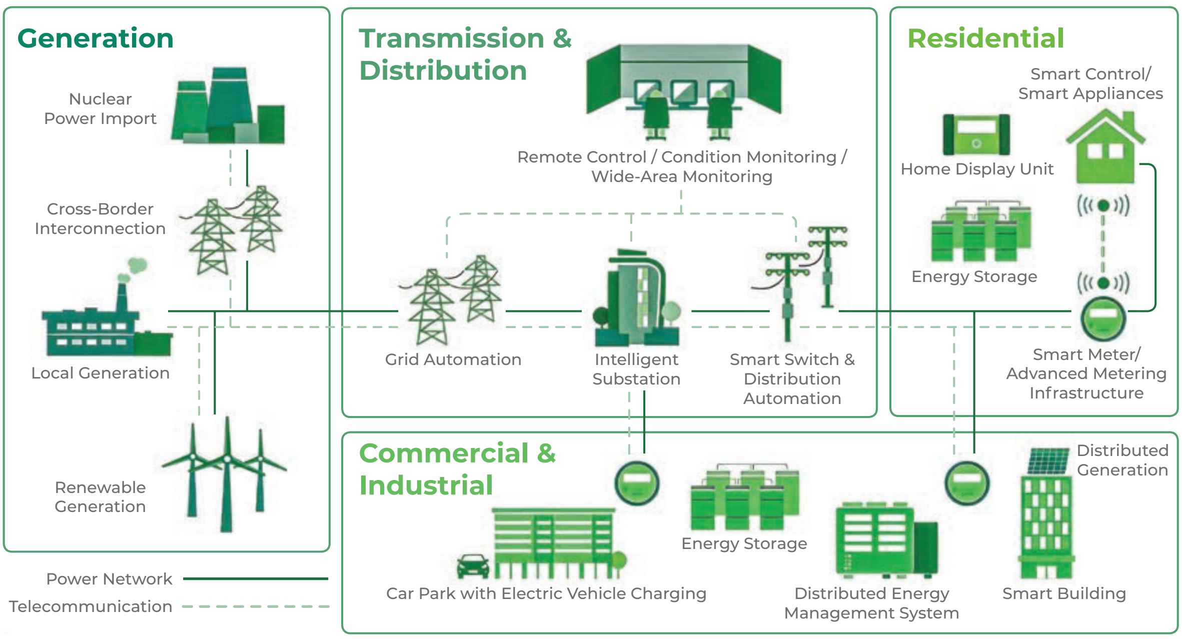


Figure 1: Overview of Smart Grid Technology (Source: ELPROCUS)

Setting the Stage

This chapter explores the technologies, opportunities, and policy implications of digitalisation and smart grids. It provides a global perspective on how digital innovation is reshaping the electricity sector and identifies the critical elements that define success — from artificial intelligence and blockchain to regulatory frameworks and consumer behaviour.

The sections that follow will:

- Clarify what digitalisation and smart grids are — and what they are not
- Examine enabling technologies and their practical applications
- Highlight case studies of successful implementation
- Discuss challenges, including cybersecurity and equity
- Offer insights into policy, regulation, and strategic outlooks

The digital transformation of energy is not a distant future — it is happening now. Understanding its mechanisms, benefits, and boundaries is essential for anyone seeking to navigate or influence the new energy paradigm.

Understanding Smart Grids and Digitalisation

In order to grasp how digitalisation is transforming energy systems; we first need to understand the key concepts at the heart of this change: the smart grid and the process of digitalisation itself. These two terms are often used together, but they refer to distinct yet interconnected ideas. This section defines both, highlights their interdependence, and clarifies how they diverge from the legacy systems of the 20th century.

Smart Grids: Power Systems That Think and Adapt

A smart grid is a modernised electricity network that integrates digital communication and automation technology to monitor, predict, and respond to fluctuations in electricity supply and demand in real time. Unlike traditional grids, which are designed primarily for one-way power delivery, smart grids support bi-directional flows of both electricity and data.

Key characteristics of a smart grid include:

- **Advanced sensing and measurement** (e.g., smart metres, phasor measurement units)
- **Automated control systems** that manage distribution and voltage levels
- **Real-time communication** between system operators, distributed energy resources, and end-users
- **Decentralised generation integration**, including renewables and storage.
- **Consumer participation**, allowing demand-side management and local production.

This shift allows for greater flexibility, higher efficiency, and better resilience in managing electricity — all of which are critical in an increasingly electrified and decarbonised world.

Digitalisation: The Intelligence Engine Behind Energy Systems

Digitalisation refers to the broader transformation enabled by embedding information and communication technologies (ICT) into energy infrastructure. While the smart grid is a key outcome of this transformation, digitalisation extends beyond physical grid upgrades.

It encompasses:

- **Data collection and analytics** for predictive insights
- **Machine learning and AI applications** in forecasting and control
- **User platforms** for real-time energy monitoring and flexible billing
- **Integration of Internet of Things (IoT)** devices for equipment and environment monitoring
- **Blockchain** technologies for transaction transparency in energy markets

In essence, digitalisation enables intelligent decision-making across the entire energy value chain — from power generation to consumption — by converting analogue operations into dynamic, data-driven processes.

Smart Infrastructure Meets Digital Intelligence

Smart grids and digitalisation are not synonymous, but they are inseparable in practice. The smart grid is the infrastructure layer — the physical and operational transformation of the grid — while digitalisation provides the intelligence and interactivity that make it "smart."

Digitalisation also allows the grid to interface with non-grid actors, such as consumers with rooftop solar, electric vehicle fleets, or community batteries. In this way, it transforms the grid from a closed system into an open platform for energy innovation.

A Technological and Institutional Break from the Past

Critically, the smart grid is not simply an enhancement of old systems — it represents a paradigm shift. Traditional grids were based on centralised control, static pricing, and predictable demand patterns. In contrast, the smart grid must accommodate:

- Variable renewable generation
- Dynamic consumption behaviours
- Multi-directional energy flows
- Cyber-physical risks

This makes the shift to smart grids not only a technical challenge but a strategic and institutional transformation — one that requires new thinking in policy, regulation, economics, and user engagement.

Understanding the difference between digitalisation and smart grids is essential for grasping how the electricity system is evolving. Digitalisation is the process; smart grids are the product. Together, they form the foundation for a flexible, resilient, and low-carbon energy future.

AI in Grid Optimisation

Modern power grids generate enormous streams of data, from smart metres and sensors to weather forecasts and electricity markets. Artificial intelligence (AI) offers powerful tools to analyse this data and make the grid intelligent, more efficient, dependable, and resilient. In an intelligent grid, AI acts as the "brain" – continuously evaluating grid conditions and taking actions to balance supply and demand in real time. This capability is crucial as renewable energy sources like solar, and wind introduce more variability into the system. AI algorithms can forecast fluctuations and adjust the grid pre-emptively, helping operators integrate renewables while maintaining stability. In short, intelligent grids can optimise energy generation and distribution to meet consumer needs with minimal waste.

One key application of AI in an intelligent grid is real-time monitoring and automated control. AI systems ingest live data from across the network – voltages, power flows, equipment temperatures, etc. – and quickly recognise anomalies or looming problems. For example, if an AI detects a transformer overloading or a sudden voltage dip, it can automatically reroute power or shed non-critical loads to prevent an outage. Traditional grids often only discover problems after equipment fails or customers lose power, whereas an AI-enabled grid can respond instantaneously to mitigate issues. This enhances reliability by reducing downtime; the grid becomes self-healing and more resilient to disturbances. Another vital role is demand forecasting and demand response. AI excels at analysing historical consumption patterns, real-time usage, weather conditions, and other factors to predict how much electricity will be needed soon.

These predictive analytics allow grid operators to anticipate surges or drops in demand with greater accuracy than traditional methods. By knowing about an upcoming peak in demand, the utility can start up additional generators or import power ahead of time. Likewise, if a surplus of solar energy is expected at noon, AI can signal battery storage systems to charge up or adjust controllable loads. AI-driven demand response programs even work on the consumer side: for instance, an AI might signal smart thermostats or electric vehicle chargers to temporarily reduce consumption during

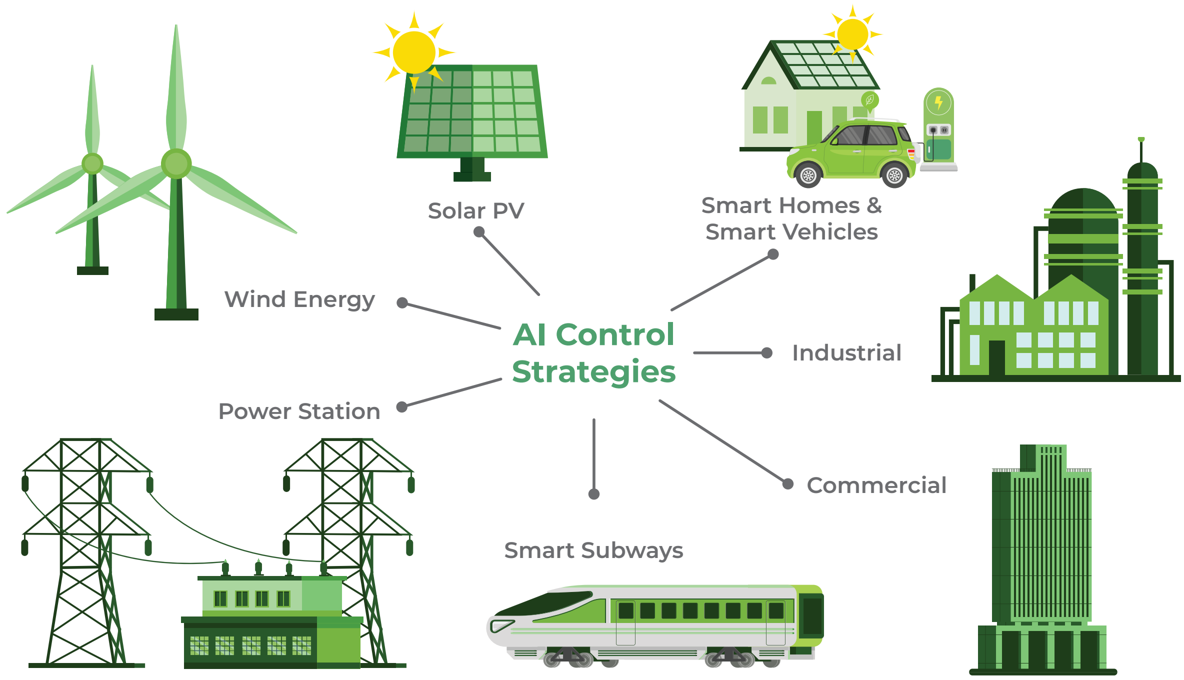


Figure 2: Intelligent grid AI control schemes (Source: United States Environmental Protection Agency 2024)

a peak period in exchange for incentive. This flexibility helps prevent grid overloads and minimises the need for costly standby power plants, saving money and reducing emissions.

Integrating renewable energy is a flagship benefit of AI in grid optimisation. Renewable sources are clean but intermittent – solar panels only produce when the sun shines, and wind turbines when the wind blows. This variability can cause supply-demand mismatches (often illustrated by the famous "duck curve" of solar over-generation midday and high demand in the evening). AI addresses these challenges by forecasting renewable output and coordinating resources accordingly. For example, machine learning models can predict tomorrow's solar generation based on weather forecasts, then schedule other power plants or storage systems to fill the gaps. If a windy afternoon is expected to produce excess energy, an AI system might store that surplus in batteries or even electric vehicles, then discharge it later when the wind calms. By orchestrating supply in this intelligent way, AI enables much higher percentages of renewables on the grid than would otherwise be possible, accelerating the transition to clean energy.

AI is also optimising the operational efficiency of the grid. In generation, AI algorithms tune power plant performance and maximise the output from each fuel source (for instance, by adjusting the tilt of solar panels or the dispatch of hydro plants). In transmission and distribution, AI can reduce losses by optimally switching network configurations and controlling voltages. It can even differentiate between minor disturbances and serious faults, enabling automated switching that isolates only the affected section instead of causing widespread outages. Predictive maintenance is another area: AI analyses patterns (like sensor data on transformer oil temperature or vibration in power lines) to predict equipment failures before they occur. Utilities can then replace or fix components proactively, avoiding unplanned outages and extending asset life. This shift from reactive to initiative-taking maintenance, guided by AI insights, improves dependability and lowers costs.

In sum, AI is becoming the digital maestro of modern grids. It brings the ability to process vast data and respond in milliseconds, which is something humans alone cannot do on a scale.

The result is a grid that can self-optimise – balancing load, integrating renewables, reducing outages, and running more efficiently overall.

Real-world examples are already emerging for instance, national grid operators

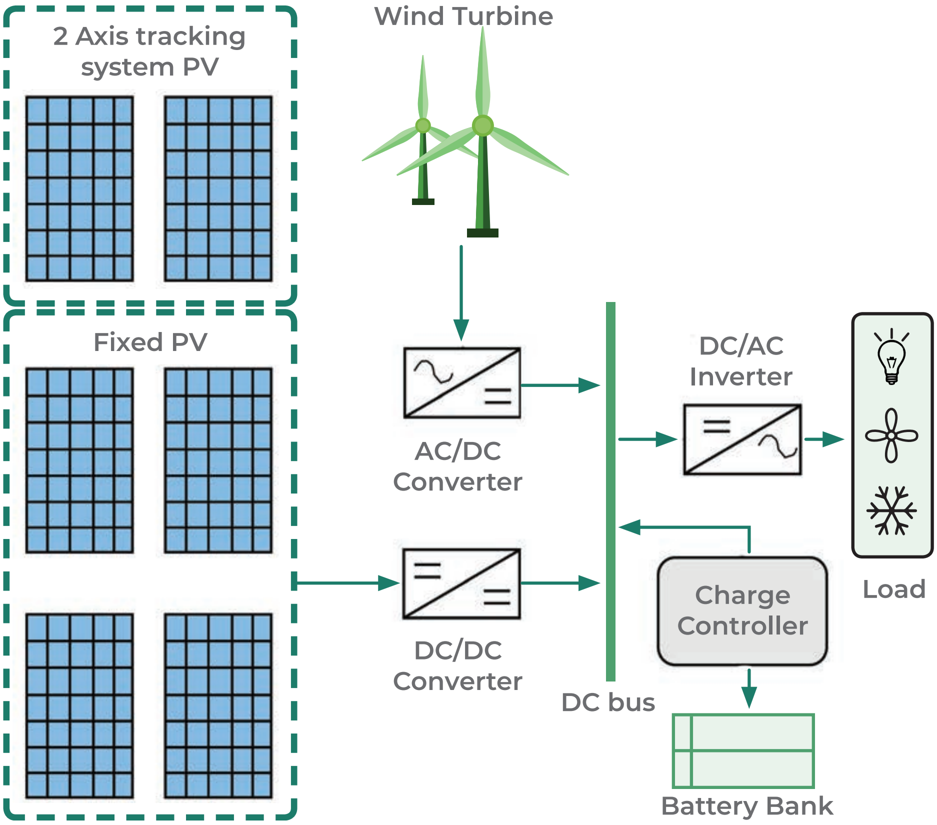


Figure 3: Advanced Metering Infrastructure (Source: MDPI 2024)

use AI-based forecasting to manage wind and solar power surges, and some utilities employ AI-driven "virtual power plants" that aggregate and control many small resources (like home batteries and smart appliances) as a single optimised unit. As these technologies mature, AI in grid optimisation is expected to play an increasingly pivotal role in delivering reliable, affordable, and clean electricity.

Blockchain and Energy Decentralisation

The rise of distributed energy resources – like rooftop solar panels, community wind turbines, and home battery storage – is transforming consumers into prosumers (both producers and consumers of energy). This decentralisation of power generation calls for new ways to coordinate countless small energy transactions. Blockchain technology offers a promising solution by providing a secure, transparent ledger for tracking energy exchanges without a central intermediary. In a traditional grid, a utility or retailer sits in the middle of every transaction; in a decentralised grid, blockchain can enable a peer-to-peer energy marketplace where participants trade energy directly with one another.

One of the most talked-about applications is peer-to-peer (P2P) energy trading. Imagine a neighbourhood where some houses have solar panels that generate excess electricity, while others need to buy extra power. Instead of routing all energy through a big utility company, neighbours could trade among themselves. Blockchain makes this possible by keeping an immutable record of energy transactions and automatically executing trade agreements via smart contracts. A real-world example is the Brooklyn Microgrid project in New York: there, residents with solar panels sold excess energy to their neighbours using a blockchain platform, in one of the first trials of community energy trading. Such local energy markets can improve efficiency (less energy lost in long-distance transmission) and reward those investing in cleaning generation. Similar pilots have occurred globally – from Australia's Power Ledger trials to European sandbox projects – all demonstrating that blockchain can securely manage many small trades and balance local supply and demand.

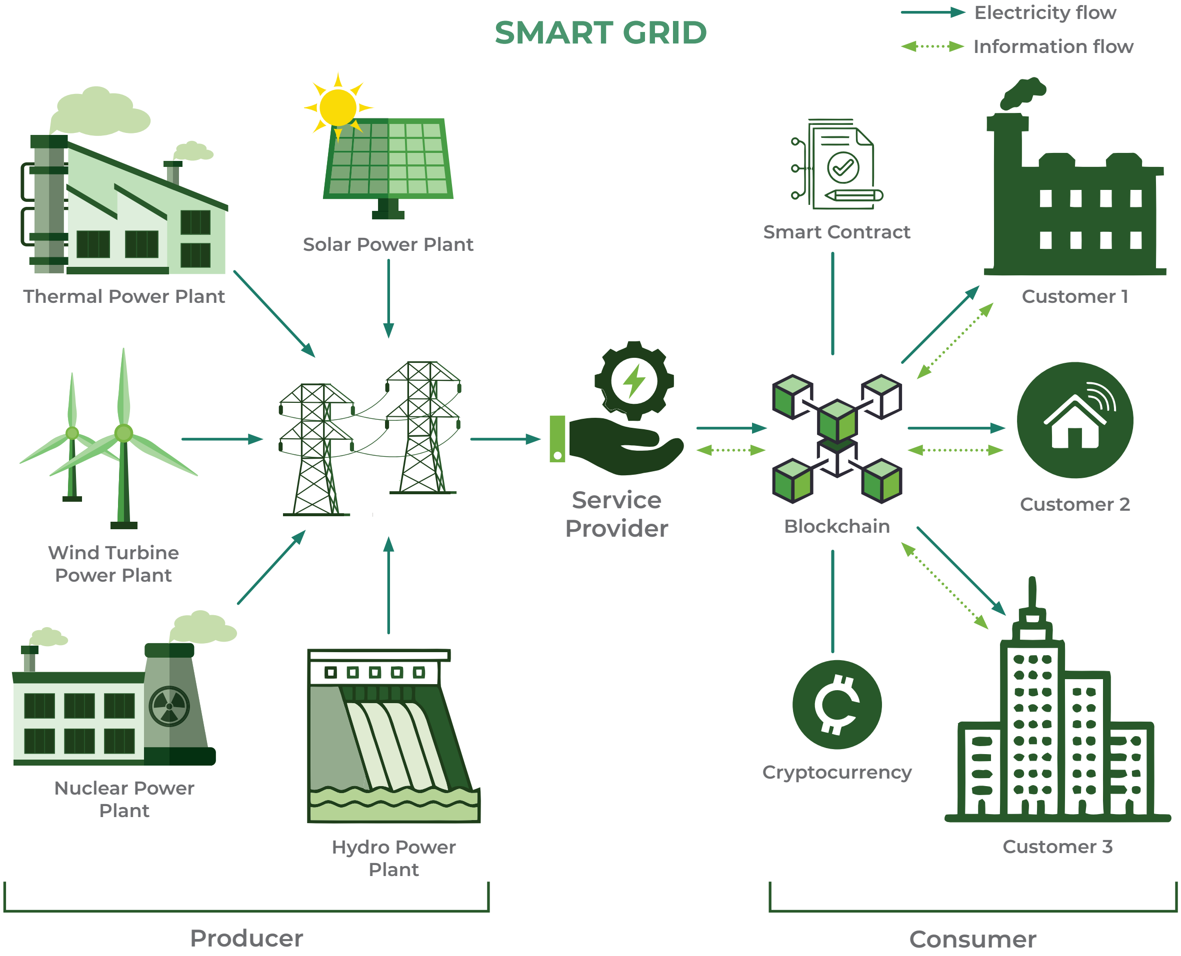


Figure 4: System Model of Blockchain-Based Stackelberg Smart Grid Environment (Source: MDPI 2022)

Blockchain's usefulness goes beyond just neighbour-to-neighbour sales. It can underpin microgrids and community energy systems. A microgrid (such as on a campus or an island) may contain several generators and consumers operating semi-autonomously. Using blockchain, the participants in a microgrid can automatically record how much power each entity generated or consumed and settle payments accordingly, all without manual billing. For example, on the Danish island of Bornholm (a testbed for advanced grids), a blockchain system could help manage energy trading between homes, EV chargers, and wind turbines as part of the island's smart grid experiments. By decentralising data and verification, blockchain builds trust among participants who might not fully trust each other – they trust the ledger instead. Smart contracts (self-executing agreements on the blockchain) can encode grid rules or tariffs: if a battery provides power to the grid at 6 PM, a smart contract can automatically pay the owner the agreed rate. This reduces administrative overhead and speeds up transactions to real-time.

Another benefit is transparency with privacy. All transactions on a blockchain are recorded and traceable, which could help in certifying renewable energy or carbon credits. For instance, when a prosumer sells 100 kWh of solar energy on a blockchain system, it could automatically generate a renewable energy certificate with a unique cryptographic proof. This can prevent double counting of green power and assure buyers that the energy is indeed renewable. At the same time, modern blockchain designs (using encryption or permissioned ledgers) can protect personal data – so participants remain pseudonymous, and their energy usage patterns are not exposed, addressing some privacy concerns. The World Economic Forum identified dozens of emerging blockchain use cases in energy, including managing supply chains for grid equipment and facilitating investment in solar projects via tokenisation. But the peer-to-peer trading and decentralised management of energy assets remain the most transformative ideas.

Despite its promise, blockchain in the energy sector is not without challenges. Early blockchain systems (like Bitcoin) were energy-intensive – a clear irony for applications in clean energy – but newer blockchain platforms and consensus algorithms (e.g., proof-of-stake) are far more efficient, making them more suitable for grid use. There are also regulatory questions: in many regions, only licensed utilities can sell power, so rules must evolve to allow community trading or at least pilot projects (some countries have introduced regulatory sandboxes for this). Furthermore, achieving interoperability and industry standards will be important so that multiple energy blockchains or platforms can work together, rather than creating isolated islands. Scalability is another factor – a national grid involves millions of transactions; new blockchain technologies claim to manage high transaction volumes, but these need to be proven in practice.

In summary, blockchain can be seen as the digital trust infrastructure for a decentralised energy world. It enables a more democratic energy system where many players can participate, from a homeowner selling solar power to a community battery providing grid services. By cutting out intermediaries, it can reduce transaction costs and empower consumers to source cheaper, cleaner energy directly. The combination of blockchain with the Internet of Things (smart appliances, EVs, etc.) could usher in transactive energy networks – an "energy internet" where devices trade energy or flexibility autonomously. As the technology matures and if supportive policies are in place, blockchain-based decentralisation could complement the intelligent grid, making the future energy system more open, efficient, and resilient.

Case Studies: Lessons from Leading Countries

Different countries around the world have pioneered various aspects of smart grids and digital transformation of electricity. By examining a few leading examples, we can glean lessons learned and best practices that inform the global transition. Here we highlight several countries and what their experiences teach about implementing digital smart grids:

United States – Driving Adoption through Investment and Innovation

The U.S. smart grid strategy has combined significant federal investment with a diverse range of utility-led initiatives. A major turning point was the 2009 American Recovery and Reinvestment Act (ARRA), which allocated $4.5 billion to grid modernisation. This launched the Smart Grid Investment Grant program, channelling nearly $8 billion in public-private funding into nearly one hundred projects nationwide. The result was a rapid deployment of smart technologies—by 2015, around 65 million U.S. customers had smart metres, reaching this milestone four years ahead of projections without the stimulus.

This experience highlights the power of policy-driven acceleration: strong government funding and incentives can significantly speed up infrastructure adoption. The U.S. also fostered innovation through pilot projects that assessed technologies like synchro phasors, distribution automation, and smart customer systems. These pilots produced valuable insights and informed broader rollouts, supported by platforms like SmartGrid.gov for knowledge sharing.

Consumer engagement was another critical focus. Utilities trialled time-based pricing models and studied customer behaviour, with simple programs like peak-time rebates showing strong participation and retention. However, challenges emerged, including ensuring system interoperability and addressing consumer scepticism—some communities resisted smart metres over privacy or health concerns, prompting improved outreach.

Overall, the U.S. case demonstrates that large-scale investment, experimentation, and transparent learning can catalyse smart grid transformation, while also underscoring the need for continued coordination, communication, and trust-building.

SMART GRID INVESTMENT GRANT (SGIG) PROGRAM OVERVIEW

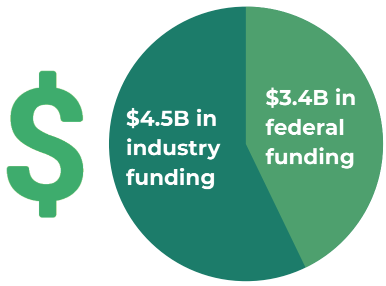
SGIG PROGRAMS AND FUNDING

99
completely selected projects

228
participating utilities and organizations

6
years (2010–2015)

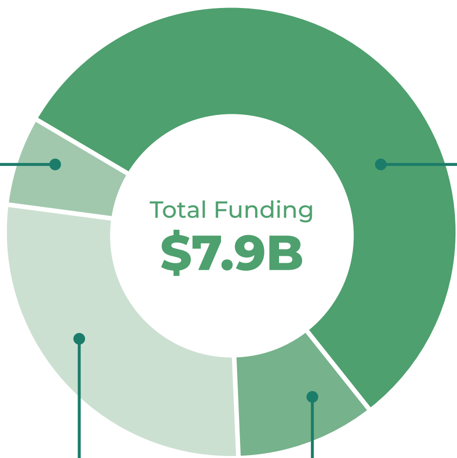
$7.9B
public/private investment



ARRA funding was matched or exceeded dollar for dollar by recipients.

SGIG PROJECT TECHNOLOGY AREAS

Electric Transmission System
$507M



Advanced Metering Infrastructure
$4.44B

Electric Distribution System
$2.19B

Customer Systems
$780M

Figure 5: Smart Grid Investment Grant Program Overview (Source: United States Department of Energy 2016

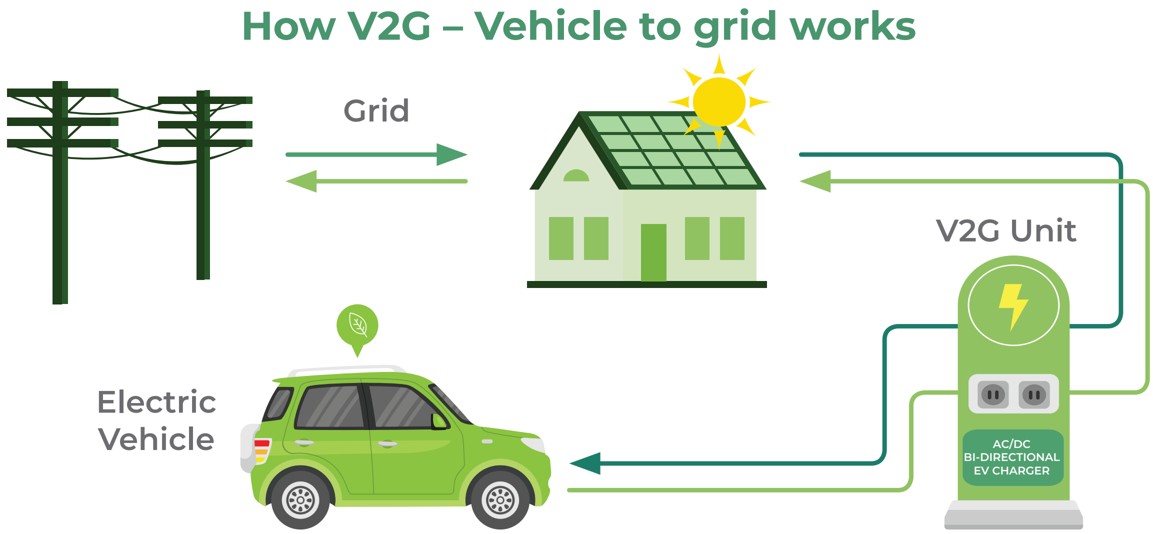


Figure 6: Vehicle to Grid Technology (Source: Servotech 2023)

Denmark – Integrating Renewables through Flexibility and R&D

Denmark is a country often cited as a smart grid frontrunner, largely because it has had to find ways to manage world-leading wind power penetration. As of the mid-2020s, Denmark frequently generates around 50% or more of its electricity from wind turbines. This feat comes with the challenge of balancing a small grid with big fluctuations when the wind blows. Denmark's lesson is that digitalisation and flexible management are essential for integrating renewables. The country invested heavily in smart grid research and demonstration projects – in fact, a European mapping found that as of 2013 Denmark had the highest number of smart grid R&D and demo projects per capita in Europe, and the most balanced portfolio of research vs implementation projects. A flagship project was EcoGrid EU on the island of Bornholm. Bornholm, with around 40,000 residents, was turned into a living lab for smart grids. The EcoGrid project demonstrated one of the world's first real-time, market-based control systems at the distribution level. In this trial, households were equipped with smart controllers and pricing signals every 5 minutes, allowing appliances (like water heaters and heat pumps) to adjust consumption based on wind availability and price. The impressive result: individual consumers automatically helped balance wind power swings by responding to price changes, without manual intervention. The island's grid, with ~50% renewables, maintained stability through this novel approach.

Lesson: dynamic pricing and engaged consumers (aided by automation) can function as a powerful tool to integrate renewables. Denmark also explored vehicle-to-grid (V2G) with electric cars, and cross-sector integration (using excess wind for electric heating, etc.). The overall Danish experience emphasises flexibility: both in grid hardware (automated switches, advanced forecasting) and in market design (encouraging rapid response to grid conditions). It also shows the value of small-scale trials in a real network environment to de-risk innovations. Denmark's success in managing variability is a template for other countries increasing their renewable mix.

Italy – Nationwide Smart Metre Rollout and Beyond

Italy provides a pioneering example of scaling up a smart grid technology to an entire country quickly. Back in the early 2000s, Italy's largest utility Enel undertook the Telelegestore project – the first mass deployment of smart electricity metres in the world. Between 2001 and 2006, Enel installed about thirty-two million smart metres for almost all Italian households and small businesses. This early start meant Italy became the first country with essentially a fully digital metering system. The immediate lesson is one of vision and commitment: Enel recognised that automating metre reading and enabling two-way communication would save operational costs (no more manual reading, remote connect/disconnect) and improve outage management. Indeed, they saw reduced losses and faster reconnection times, which translated into economic benefits for the utility and consumers. From a policy viewpoint, Italy's regulators allowed Enel to recover the costs through tariffs, justified by the efficiency gains – a model that other countries later followed. An important outcome of Italy's rollout is how it opened the door for advanced services: once the metres were in place, Italy could more easily introduce time-of-use pricing (many Italians are now on multi-tier tariffs that encourage off-peak usage) and detect fraud or losses in the system. It also provides a platform for future demand response programs. The Italian case study teaches the importance of future-proofing infrastructure: by installing metres with communications and upgradable software, they set a foundation for ongoing innovation (Italy is now onto its second generation of smart metres with even more functionality by 2025). The scale of Italy's deployment also taught the global community about project management and consumer communication at scale – Enel had to educate the public on the new metres and ensure a smooth installation process across millions of premises, which they managed with notable success. Other countries (like France, UK, and Australia) studied Italy's approach when planning their own national rollouts.

South Korea – High-Tech Testbeds and Government Planning

South Korea has embraced smart grids as part of a national strategy for green growth and technology leadership. A notable effort was the Jeju Island Smart Grid Testbed (2009–2013), one of the largest and most comprehensive smart grid demonstrations globally. On Jeju, Korean companies and the government collaborated to trial a bit of everything: smart homes with appliances responding to prices, EV charging infrastructure and V2G, renewable integration into an isolated grid, energy storage, and even blockchain-based trading systems in later phases. The Jeju project's lesson is the benefit of an integrated approach: rather than test one technology in isolation, Korea created a microcosm of a future smart energy ecosystem to see how all the pieces interact. This helped them identify interoperability issues and refine standards. Following the testbed, South Korea committed to a national smart grid roadmap, aiming for full nationwide deployment of smart metres and extensive automation by the late 2020s. They are also a world leader in energy storage deployment on the grid, often cited as an example of using batteries to enhance flexibility alongside digital control. A key takeaway from Korea is the role of central planning and industry coordination. The government set clear targets and funded R&D, while Korean industry (e.g., KEPCO, Samsung, LG) developed technologies they could later export. They also worked on the regulatory side, for example adjusting rules to allow frequency regulation markets where batteries and smart resources can be paid for grid support. Korea's experience underscores that smart grids can be a pillar of industrial policy as well as energy policy – investing early can give a country a head-start in a growing global market, and at the same time improve domestic energy efficiency and security.

Other Noteworthy Mentions

- **Australia:** Regions in Australia, such as South Australia and Queensland, have become testbeds for managing high rooftop solar penetration and Distributed Energy Resources (DERs). Key lessons include the use of volt-var control and the development of standards for smart inverters to autonomously manage voltage fluctuations. Australia has also piloted "dynamic operating envelopes," which digitally adjust solar export limits in real time based on grid capacity. These innovations demonstrate how smart controls and consumer cooperation can enable effective DER integration at scale.
- **China:** The world's largest smart grid deployment in sheer numbers, China by the late 2010s had installed well over five hundred million smart metres. State Grid Corporation of China invested massively in ultra-high-voltage transmission and wide-area monitoring systems, leveraging digital tech to manage a vast network and enable renewable integration (especially large wind/solar in remote areas). A lesson from China is standardisation and scale – they developed national standards for equipment and communications (often proprietary to State Grid), which allowed them to deploy rapidly. However, some critique that their focus was more

on top-down control than on empowering consumers; even so, they are now exploring things like demand response and electric vehicle smart charging as those become pressing issues.

Each of these case studies yields insights: the U.S. highlights funding and innovation; Denmark shows the power of flexibility for renewables; Italy demonstrates early adoption and scaling; South Korea illustrates comprehensive planning and tech integration. A common thread is that smart grids are not a one-size-fits-all recipe – each region tailored its approach to its unique drivers (be it reliability, renewable integration, loss reduction, etc.). Yet, all underscore the importance of policy support, stakeholder engagement, and a willingness to experiment. By sharing these global lessons, other countries can avoid pitfalls (like underestimating cybersecurity or consumer concerns) and accelerate their own smart grid journeys.

Smart grids are not a one-size-fits-all recipe – each region tailored its approach to unique drivers.

Risks and Barriers to Digital Grid Adoption

Transitioning to a digital, smart grid is not without its hurdles. Even as the benefits are clear, there are significant risks and barriers that can slow or undermine the adoption of digital grid technologies. It is essential to identify these challenges and address them proactively. Here we discuss the main categories of obstacles:

Cybersecurity Threats

A key risk of grid digitalisation is heightened vulnerability to cyber-attacks. Each smart metre, sensor, or connected control system introduces a new potential entry point for hackers. A successful breach could trigger blackouts or market manipulation—such as falsified metre readings or mass disconnections. The 2015 Ukraine grid attack underscored how control systems can be hijacked to disrupt electricity supply. As grid connectivity expands, utilities face growing threats not only from hackers and ransomware criminals but also from state actors. This risk makes both regulators and utilities wary of rapid deployment. The industry has responded with encryption, intrusion detection, and network segmentation, but cyber defence remains an ongoing and costly challenge. Smaller utilities may lack the resources or expertise to fully secure these systems, further slowing adoption. Ultimately, overcoming this barrier requires both robust technical solutions and strong stakeholder confidence in grid security.

Data Privacy and Consumer Acceptance

Smart grids collect detailed data on households and businesses. Privacy concerns are a barrier in two ways. First, consumers who are aware might resist devices like smart metres, worrying that "Big Brother" is monitoring their daily routines. This happened in some rollouts: a small fraction of customers refused smart metres or raised health and privacy objections (some even citing unfounded claims like radio frequency emissions causing illness). This can become a political issue, with local groups lobbying against smart metre mandates. Second, regulators might slow things down by insisting on comprehensive privacy frameworks before green-lighting certain technologies – which is good practice, but the process of crafting those policies can be slow. Overcoming this barrier requires transparent communication: utilities need to clearly explain what data is collected and how it will be used (and not used) and give consumers some control or benefits from that data (for example, providing useful insights back to the consumer builds goodwill). Public trust is crucial. If the populace is sceptical or fearful, projects can face delays or even moratoriums. One lesson learned is to engage communities early – pilot programs that involve volunteer participants who then champion the tech can help sway public opinion.

High Upfront Costs and Legacy Systems

Upgrading to a smart grid can require substantial capital investment. Installing smart metres for every customer, deploying sensors on distribution lines, building communication networks, and purchasing new software systems – these are high upfront costs that not all utilities (or their regulators) are eager to bear. For instance, a utility may need to invest hundreds of millions in smart metres and networking. While these costs are typically offset over time by operational savings and efficiencies, the upfront financial burden can be a major deterrent. Securing regulatory approval for cost recovery hinges on a clear, compelling business case—without it, approval may be denied. Smaller or financially weaker utilities may face even greater challenges in funding such initiatives. Relatedly, many utilities have extensive legacy equipment that is not easily retrofitted for digital control. Replacing or integrating old infrastructure (some relays or transformers in use might be 40+ years old) with modern systems is complex. These technical integration challenges can cause delays and cost overruns, which become barriers as boards and investors fear project risks. Financial risk aversion can slow adoption – stakeholders might prefer to wait for costs to come down or technologies to mature further.

> Implementing smart grids is often said to be 20% technology, 80% organisation – the bigger challenge lies in people and processes.

Interoperability and Technology Maturity

There is a wide array of vendors and technologies in the smart grid space. A utility might worry about picking the "wrong" system – for instance, installing a certain brand of smart metre only to find in 5 years that it is incompatible with newer standards or that the vendor went out of business (leaving them with unsupported tech). The absence of universal standards in some areas (or the lag in adopting them) means interoperability is a real concern. Utilities often conduct lengthy trials to ensure different pieces of their smart grid puzzle will work together, which slows full deployment. Moreover, not all technologies are fully mature. For instance, AI for grid control is still emerging – some operators might not trust an algorithm to run the show without more proven results. Cultural resistance within utility companies plays a role too: engineering staff who have operated one way for decades might be sceptical of relinquishing some control to automation or new analytics. They might cite "unproven reliability" or fear that new systems will introduce unforeseen problems. Overcoming this barrier requires not just technology development but change management and training – utilities need to train their workforce to work with new tools and build confidence in those tools. It is often said that implementing smart grids is 20% technology, 80% organisation (people and process changes).

Regulatory and Market Barriers

Regulation can be a double-edged sword – while supportive policy can accelerate smart grids, outdated or inflexible regulation can hinder it. In some regions, the lack of a mandate or incentive for smart metres means utilities do not bother deploying them. If a utility's profits are tied to old cost-of-service models, they might see no financial upside in investing in digital efficiency which could reduce energy sales. Also, where the utility and grid operator roles are separated (like in parts of Europe where retailers supply power and separate companies manage networks), coordinating who pays for and benefits from smart grid investments can be tricky. Market structure issues can also be barriers: for example, if there is no way for demand response or storage to earn revenue in the market, then businesses will not invest in those even if technology is available. We are seeing improvements here (with new market products for flexibility, etc.), but policy lags can slow adoption of technologies that depend on market signals. Another example: in some places, strict rules prevented third parties from accessing metre data, which in turn stifled the development of consumer energy apps or services. The barrier is the slow pace of regulatory change – energy is a critical service, so regulators are understandably cautious. But that caution can translate to long pilot phases, incremental rollouts, or waiting for others to move first.

Workforce and Skill Gaps

Digital grids require a different skill set than traditional electrical engineering alone. Utilities now need data scientists, IT specialists, and cybersecurity experts. There is a human capital barrier in that the workforce must evolve, and there's competition for talent with tech industries. Training existing personnel is essential but takes time and resources. A utility might be hesitant to adopt a sophisticated analytics platform if they do not have people who know how to interpret and act on the data. Likewise, grid operators must learn to work with AI decision-support tools – a change some may resist, feeling it threatens their role. Bridging the skills gap is an often-underappreciated barrier; it is not as headline-grabbing as cyber threats, but if utilities cannot staff the transformation, it will stall. Partnerships with universities and new training programs are the way this is being addressed, but again, it is a gradual process.

Infrastructure Limitations

In some developing or rural areas, even the basic supporting infrastructure for a digital grid – namely reliable telecommunications – may be lacking. Smart devices cannot communicate without reliable connectivity. Weak cellular networks or inconsistent internet access pose significant barriers to deploying IoT solutions across the grid. Utilities might have to invest in private communication networks (like radio systems or fibre) which adds cost and complexity. Also, power systems that suffer from frequent outages or voltage fluctuations might first need traditional upgrades before layering on digital solutions. A baseline level of grid stability and communication infrastructure is essential to fully realise the benefits of smart technologies—yet this foundation is not consistently available across all regions.

Public and Political Will

Finally, a subtle barrier can be the priority (or lack thereof) that leaders and the public assign to grid modernisation. When everything is working reasonably, grid investments are often "invisible" to consumers compared to, say, roads or schools. It may be challenging to garner public support for large spending on grid projects, especially if it is passed through to bills. Without a clear understanding of benefits, customers might balk at seeing a surcharge for smart grid investments. Politicians, sensitive to electricity rates, might delay approving projects that have upfront costs. Only when a problem hits – like a major blackout or failure to integrate renewables – does it become urgent. This barrier is essentially the status quo bias: an inclination to stick with known, if suboptimal, ways rather than take risks on innovative approaches.

Addressing these risks and barriers requires a comprehensive, multi-faceted strategy. A foundational element is the implementation of robust cybersecurity frameworks from the outset, with continuous updates to address emerging threats. Initiative-taking stakeholder education and engagement are equally critical—they help alleviate privacy concerns and foster broader acceptance by clearly demonstrating tangible benefits such as reduced energy costs and enhanced grid reliability. Financial obstacles can be mitigated through innovative funding mechanisms, including government grants, public-private partnerships, and regulatory frameworks designed to de-risk private sector investment. To overcome technical and interoperability challenges, the development of industry-wide standards and systematic knowledge-sharing among utilities is essential, ensuring efficiency and avoiding duplication of effort. Finally, pilot projects serve as valuable tools to build confidence and demonstrate the viability of innovative technologies in real-world settings.

One encouraging sign is that as more projects succeed around the world, these barriers are gradually lowering. Utilities can point to peers who securely rolled out smart metres or effectively used AI for outage management, reducing the fear of the unknown. But the process is evolutionary. The smart grid transition is as much a change in mindset as in hardware and software. Overcoming the barriers will require continued persistence, collaboration, and learning from failures as well as successes.

Conclusion

As we navigate the complexities of the 21st century, the intersection of digital transformation and climate action emerges as a pivotal arena for innovation and sustainability. Digital technologies—ranging from data analytics and artificial intelligence to cloud computing and the Internet of Things—offer unprecedented opportunities to mitigate greenhouse gas emissions and adapt to climate change. However, realising this potential requires deliberate strategies to ensure that digital advancements contribute positively to environmental goals. The energy transition will be a twin green and digital transition.

The concept of smart grids has advanced significantly over the past two decades and intelligent grid is no longer merely a trial technology—though the degree of implementation varies greatly by country and region.

In the United States, Europe (especially Germany, France, United Kingdom, and Nordic countries), South Korea and Japan smart grids are already integrated into national or regional energy strategies. These systems include:

a) Advanced metering infrastructure (AMI)
b) Grid automation
c) Distributed energy resource (DER) management
d) Real-time analytics and demand response

In India, Brazil, China (some rural regions) and South Africa, smart grid projects exist but are often confined to urban or high-priority industrial zones. These deployments tend to be pilot-oriented or segmented (e.g., smart metres without full grid digitisation).

In some developing economies, smart grid concepts are under discussion or in early development, hindered by Infrastructure gaps, Regulatory complexity, Lack of funding or digital literacy. These nations might be testing smart metering or microgrid setups supported by international development funds (e.g., World Bank, Asian Development Bank). However, local distribution may remove the need for electricity grids in a way similar to mobile phone no longer need telephone lines.

Harnessing Digital Technologies for Climate Action

Digital tools can significantly enhance climate action by:

- **Optimising Energy Use:** Smart grids and energy management systems enable more efficient distribution and consumption of energy, reducing waste and emissions
- **Enhancing Data-Driven Decision-Making:** Advanced analytics facilitate better forecasting of climate patterns and inform policy decisions
- **Promoting Sustainable Practices:** Digital platforms can encourage behavioural changes by providing real-time feedback on energy usage and carbon footprints

These applications demonstrate the transformative power of digital technologies in achieving sustainability targets.

Addressing the Environmental Impact of Digital Infrastructure

While digital technologies offer solutions, they also pose challenges. The production, operation, and disposal of digital devices and infrastructure consume significant energy and resources, contributing to carbon emissions. For instance, data centres require substantial electricity for operation and cooling, often sourced from fossil fuels.

To mitigate these impacts, it is essential to:

- **Invest in Renewable Energy:** Powering digital infrastructure with renewable sources can reduce emissions.
- **Enhance Energy Efficiency:** Implementing energy-efficient hardware and optimising software can lower energy consumption.
- **Promote Circular Economy Practices:** Encouraging recycling and responsible disposal of electronic waste minimises environmental harm.

By addressing the environmental footprint of digital technologies, we can ensure that their deployment aligns with climate objectives.

09

CHAPTER 09

ENERGY JUSTICE, ENERGY INTENSITY, AND NDCS

Energy is a critical enabler of human development, economic opportunity, and environmental sustainability. Yet, billions of people around the world still lack reliable access to clean and affordable energy.

The 2025 review of the 2030 Agenda for Sustainable Development by the United Nations Department of Economic and Social Affairs (UNDESA), indicates that while the world continues to advance towards sustainable energy targets, the pace of growth is not fast enough. In a brief titled, “Promise in peril”, UNDESA stated that at the current pace, about 660 million people will still lack access to electricity and close to 2 billion people will still rely on polluting fuels and technologies for cooking by 2030.

Renewable sources power nearly 30 per cent of energy consumption in the electricity sector, but challenges remain in heating and transport sectors. Developing countries experience 9.6 per cent annual growth in renewable energy installation, but despite enormous needs, international financial flows for clean energy continue to decline. To ensure access to energy for all by 2030, the world must accelerate electrification, increase investments in renewable energy, develop innovative cooperative approaches and business models, improve energy efficiency and develop enabling policies and regulatory frameworks.

As nations strive to meet climate goals through their Nationally Determined Contributions (NDCs), it becomes essential to ensure that transitions toward low-carbon energy systems are not only efficient and sustainable but also equitable. Energy justice has emerged as a framework that examines how energy systems affect people differently, emphasising fairness in energy access, decision-making, and outcomes.

This chapter introduces the conceptual foundations of energy justice, focusing on its core dimensions: access, affordability, and fairness. The chapter further explores how energy intensity intersects with industrialisation, urbanisation, and poverty reduction, and examines policy and technological solutions for balancing growth with sustainability. The chapter then concludes with how equity can be mainstreamed in NDCs and outlines mechanisms for operationalising fairness in energy policy through participatory governance, equitable burden-sharing, and inclusive benefits. ▸

Defining energy justice: Access, affordability, and fairness

Understanding Energy Justice

The concept of energy justice draws from environmental justice, climate justice, and human rights discourses. It seeks to rectify energy-related inequalities by focusing on who are the stakeholders, the shareholders and the rightsholders and who benefits, who bears the burdens, and who participates in decisions about energy systems.

It is a multi-layered, human-centric theoretical approach that is typically framed around three main tenets:

- Distributional justice – equitable distribution of energy resources, benefits, and harms
- Procedural justice – inclusive and fair decision-making processes
- Recognition justice – acknowledgment and inclusion of marginalised voices and values

While the energy sector has revolutionised the world for the better in many ways, it is a double-edged sword that continues to raise a host of economic, political, and social issues across the globe. With so much inequality in the energy system, policymakers have started to recognise that such systems need to be designed in a way that combats injustices and promotes fairer energy for all.

Energy Access: A Foundation for Development

According to the International Energy Agency (IEA), nearly 675 million people lacked access to electricity in 2022, with sub-Saharan Africa accounting for more than 80% of that figure. In sub-Saharan Africa 570 million people are living without access to electricity.

The world remains off track to achieve universal access to clean cooking by 2030. Up to 2.1 billion people still use polluting fuels and technologies for cooking, largely in Sub-Saharan Africa and Asia. The traditional use of biomass also means households spend up to 40 hours a week gathering firewood and cooking, which makes it difficult for women to pursue employment or participate in local decision-making bodies and for children to go to school.

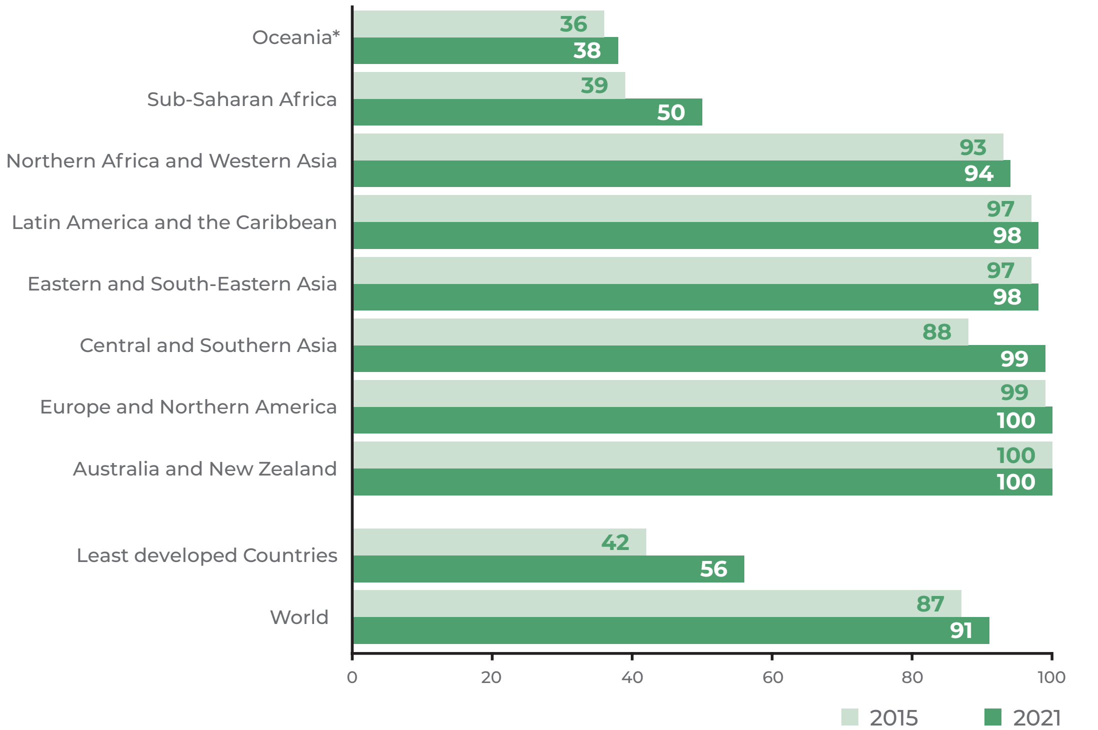


Figure 1: Proportion of Population (Percentage) With Access to Electricity, 2015 and 2021 *Oceania Figures Exclude Australia and New Zealand (Source: UNDESA)

Access to modern energy is increasingly recognised as a prerequisite for realising other rights, such as education, health, and economic participation. Barriers to universal energy access include inadequate infrastructure, rural remoteness, and gender or income inequality.

Affordability: Ensuring Economic Equity

Energy poverty affects households that cannot afford basic energy services, often burdening low-income and marginalised groups. Energy affordability is often assessed by the share of household income spent on energy, with values above 10% often indicating vulnerability. Policy solutions include subsidies, decentralised renewable energy systems, innovative business models and inclusive financing mechanisms.

Affordable and clean energy focuses on addressing the global energy challenge by contributing to providing access to reliable, sustainable, and modern energy for all. It recognises the importance of energy in powering economic development, improving living standards, and mitigating climate change.

Access to affordable and clean energy is crucial for eradicating poverty, improving health and education, promoting economic growth, and combating climate change.

Low-income households and those facing systemic barriers to building wealth, especially in the developing world, are more likely to experience energy poverty and the negative health, safety, and well-being outcomes associated with it. Efforts to ensure equitable outcomes from the energy transition require that more finance than ever be directed toward helping households afford the energy they need.

Affordability has always been a concern for consumers and policy makers, but this has been heightened in recent years by price spikes during the global energy crisis and resulting pressures on the cost of living.

According to an IEA report, consumers around the world spent nearly USD 10 trillion on energy in 2022 – an average of more than USD 1 200 per person – even after considering the subsidies and emergency support mobilised by governments. This is nearly 20% more than the average over the previous five years.

Some countries and communities experienced a much greater shock, and high prices hit the poor and vulnerable hardest, in both developing and advanced economies. The IEA pointed out that in the European Union, for example, more than 40 million people were unable to keep their homes adequately warm. As the debate on the centrality of affordability and fairness to clean energy transitions continues, the spotlight is on the affordability of energy transitions.

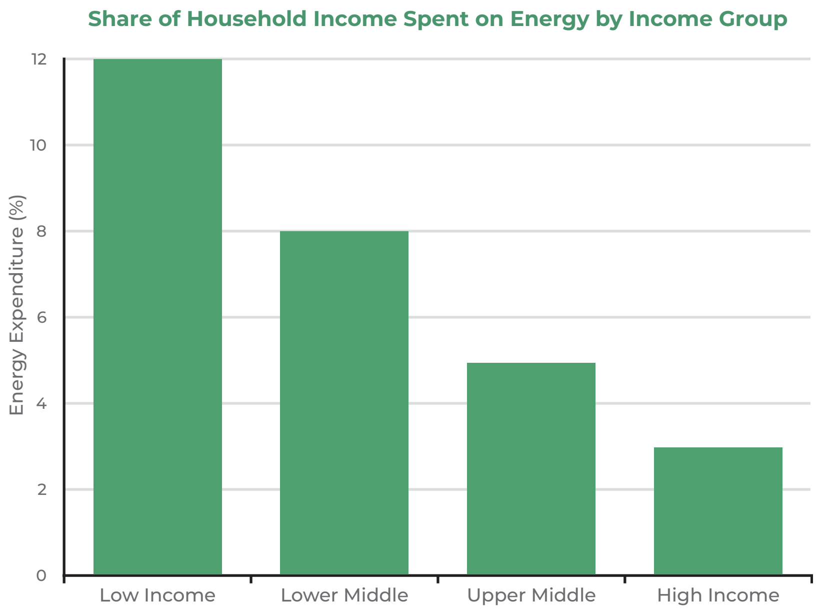


Figure 2: Share of Household Income Spent on Energy by Income Group (Source: IEA (2023), World Energy Outlook 2023)

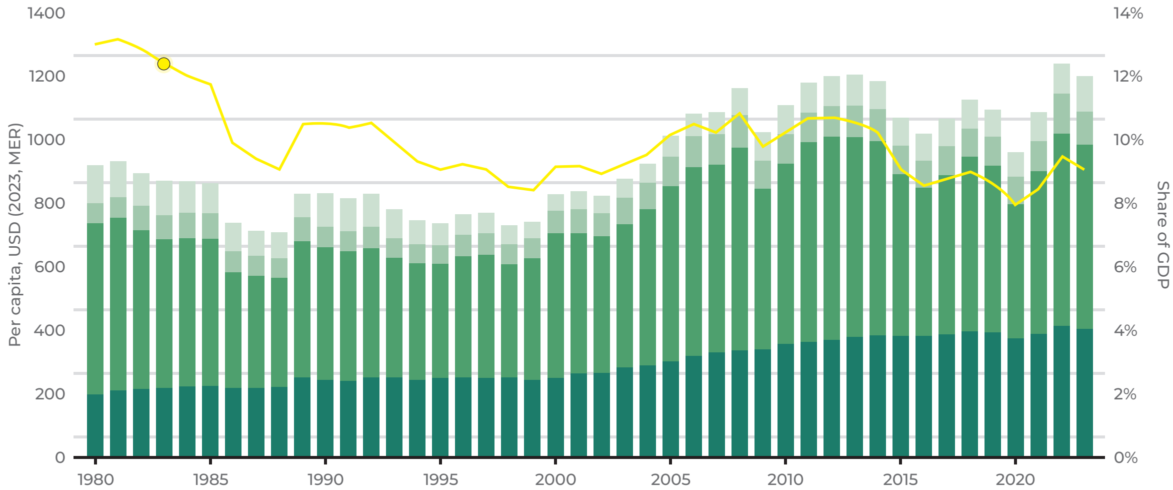


Figure 3: Global Energy Bill per Capita and as a Share of GDP, 1980-2023. (Source: IEA (2024), Global energy bill per capita and as a share of GDP, 1980-2023

Fairness in Energy Systems

In economic theory, a fair allocation is where agents are satisfied with their share of benefits and do not envy others, constituting a "just" allocation. Concerns about the fairness of the energy transition are receiving increased international attention as we approach the 2030 target for the United Nations Sustainable Development Goals (UNSDGs).

The concept of fairness in energy systems has two main components – procedural and distributional fairness. Procedural fairness focuses on inclusive and transparent decision-making, including the rights of all peoples, particularly the marginalised communities. Distributional fairness relates to how the costs, benefits and harm of energy systems are shared, particularly in clean energy transitions that can displace or exclude certain groups.

Procedural energy justice ensures fairness in low carbon energy decision making. It emphasises transparency, inclusivity, and meaningful participation of stakeholders and rightsholders in policy and project decisions. This also involves providing access to information, engaging diverse perspectives, and ensuring accountability to promote equitable processes and outcomes in energy governance.

Distributional fairness in energy system refers to the equitable allocation of both the benefits and burdens associated with energy production, distribution, and consumption. It emphasises ensuring that all social groups, particularly marginalised or vulnerable communities, have fair access to energy resources, affordable energy services, and are not disproportionately affected by environmental or economic costs such as pollution or high utility rates. This principle is central to achieving social justice within energy transitions, as it addresses historical inequalities and aims to create an inclusive energy future where no group is left behind.

Energy Intensity and the Development Dilemma

What Is Energy Intensity?

Energy intensity – defined as the amount of energy consumed per unit of economic output – is a key indicator of how efficiently a country uses energy to drive growth. For emerging economies, the challenge lies in reducing energy intensity while sustaining rapid development and improving livelihoods.

Energy intensity is commonly expressed as energy use per unit of gross domestic product (e.g., megajoules per dollar of GDP). High energy intensity often indicates inefficiencies in production, infrastructure, and energy use. Factors influencing energy intensity include industrial structure, energy source mix, technology levels, and climate.

The Growth-Sustainability Trade-off

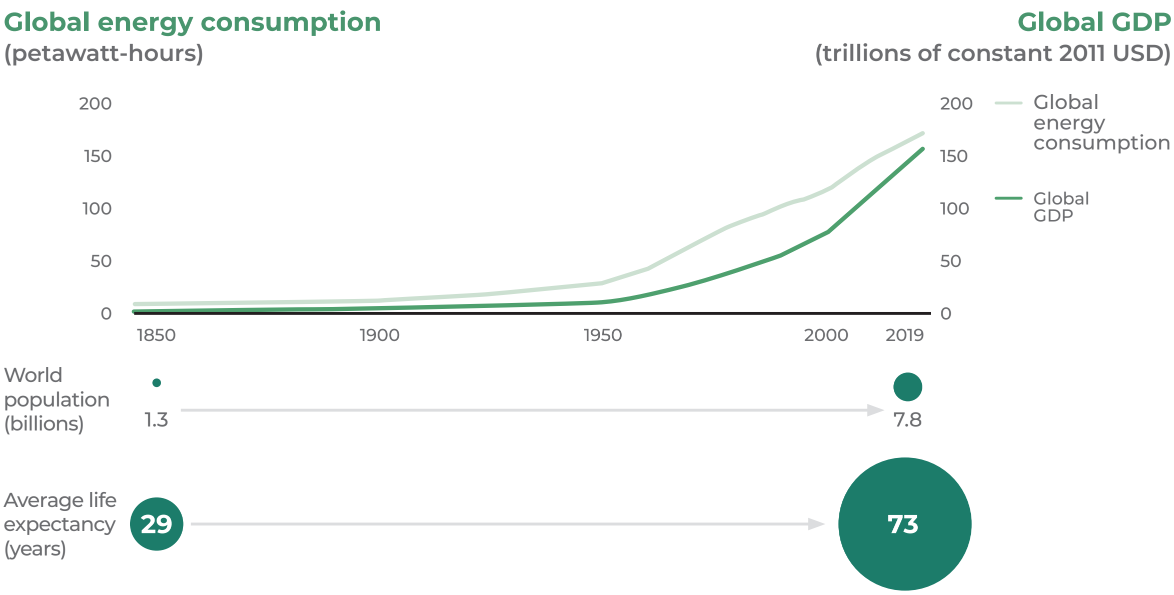
It is an undeniable fact that energy fuels the engine of economic growth. As global economies and populations continue to grow and prosper, the world faces the dual challenge to deliver affordable, reliable energy while addressing the risks of climate change. At the heart of this challenge is the fact that reliable access to energy is key to sustainable growth and high standards of living. While it is normal expectation of the people in developed economies to take access to reliable energy for granted, for many people in emerging economies, reliable access to energy remains unattainable. The imperative of avoiding the risks of climate change and addressing the societal concern for the environment defines the scale of the trade-off needed, particularly in developing countries. Meeting the growing demand for energy while also reducing greenhouse gas emissions is the central challenge of the 21st century.

Emerging economies often face a dual imperative: increasing energy consumption to power development while curbing emissions and meeting climate commitments. This creates a development dilemma:

- Rapid industrial growth can increase energy use and emissions.
- Energy efficiency improvements may be cost-intensive or technically challenging.
- Shifts to cleaner fuels can be slow due to infrastructure and affordability constraints.

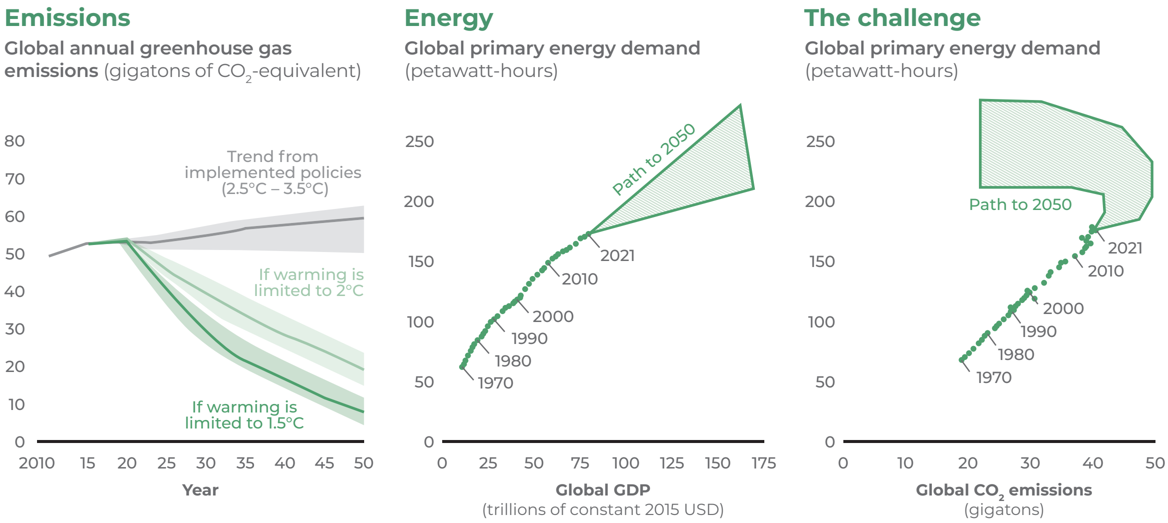
Solving the challenge will require change on an unprecedented scale and pace, including major infrastructure investments. General estimates by most analysts indicate that the world will need to nearly triple annual investment in clean energy to reach net-zero emissions by 2050. According to the IEA's Scenario for Net Zero Emissions (NZE) by 2050, the world would need to approximately double its 2022 pace of total energy investment by 2030 and sustain this level through 2050 to achieve net-zero emissions. As the global population continues to increase by 1.7 billion by 2050, mostly in the developing countries, so is the world's need and appetite for energy.

As shown in Figure 4, the global energy consumption, population, and gross domestic product have historically grown in tandem. In most developing countries, small increases in energy consumption per capita are strongly associated with significant gains in the Human Development Index (HDI). The HDI, which is a United Nations composite measure, comprising of indicators for health, education, and income,



Note: GDP is adjusted for purchasing power parity.
Sources: BP Statistical Review of World Energy 2021; Vaclav Smil, *Energy Transitions: Global and National Perspectives*, 2017; Maddison Project Database 2020, Jutta Bolt and Jan Luiten van Zanden, "Maddison style estimates of the evolution of the world economy: A new 2020 update"; World Bank; Our World in Data; Bain analysis

Figure 4: Global Energy Consumption Tracks Population and GDP Growth



Notes: Warming figures in left-side emissions chart are relative to the preindustrial period and reflect projected warming level by 2100 in each scenario; bold lines in left side emissions chart represent median estimate and shaded regions reflect a range from the 25th to 75th percentile; emissions in right-side chart reflect global CO_2 emissions inclusive of land use change and exclude non-CO_2 emissions like methane.
Sources: IPCC, Sixth Assessment Report; World Bank; Global Carbon Project; BP Statistical Review of World Energy 2022; Bain analysis

Figure 5: The Daunting Task of Bending of the Emissions Curve While Still Serving Higher Energy Demand (Source: Bain & Company Report, 2023)

supports the notion that energy is critical to human prosperity.

The extraordinarily challenging path the world must take to resolve the dual challenge of ensuring access to sustainable energy and addressing the risks of climate change is vividly shown in Figure 5. The first panel of Figure 5 shows that the world is not on track for a scenario in which the world warms less than 2 degrees Celsius above preindustrial levels, a target set in the Paris Agreement. At the same time, energy supply will likely need to increase in the coming decades to support economic growth and enhance human well-being, though efficiency gains will provide some buffer (see second panel of Figure 5). Adding these two factors together results in the target scenario shown in the third panel of Figure 5, which depicts the bending of the emissions curve while still serving higher energy demand.

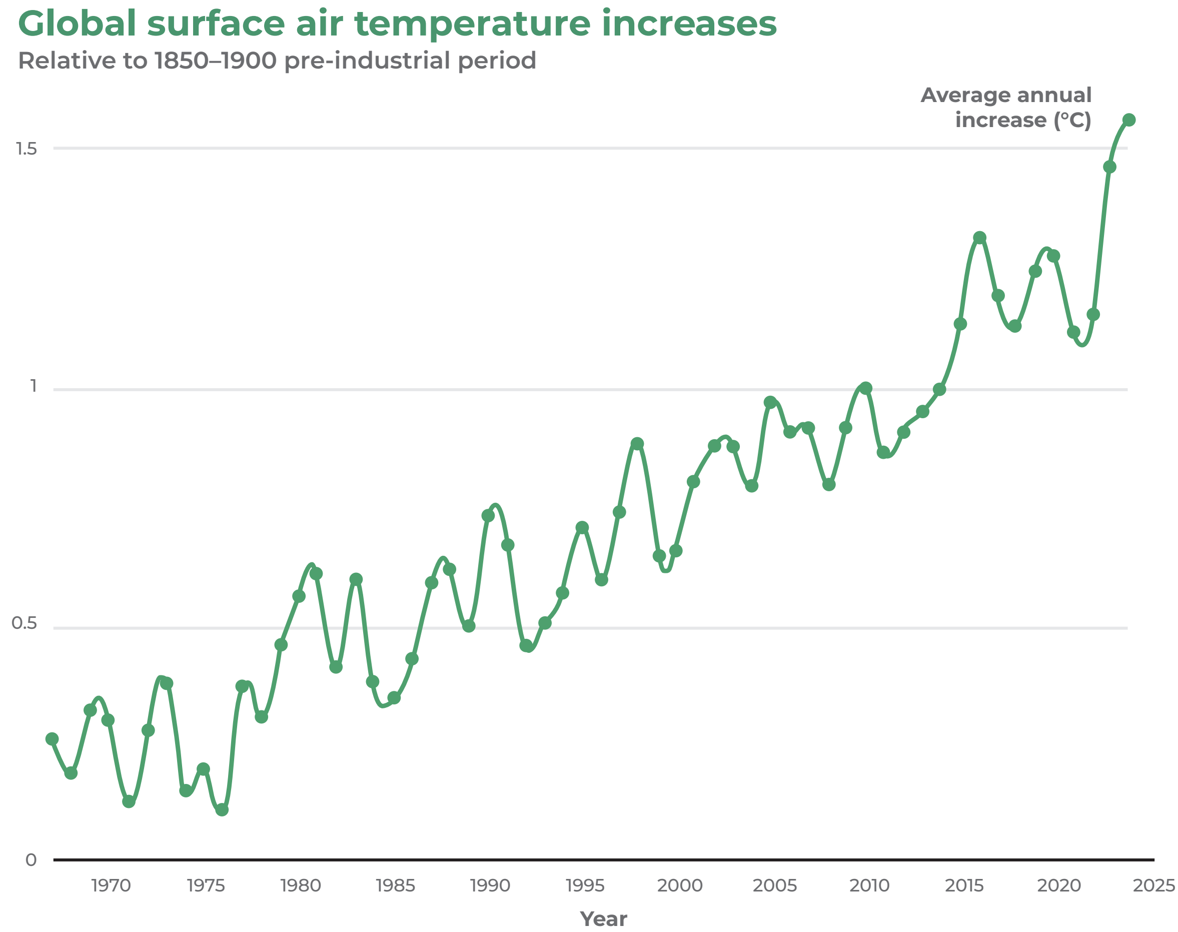
The unprecedented journey of the dual challenge of the energy transition will be different for every country. In low-income developing and emerging economies, the objective is to lift countries out of energy poverty, achieve high living standards and support industrialisation and economic development and growth in a low-carbon way (i.e., without following the historical trajectory of advanced economies). In advanced economies, it's about decarbonising the economy while maintaining high living standards and economic growth.

Strengthening NDCs to Incorporate Social Equity in Energy Transitions

What are NDCs and Why Do They Matter?

NDCs are the primary mechanism through which the Paris Agreement translates global climate ambition into national action. Through NDCs, countries articulate their climate goals and strategies. Originally introduced ahead of the 2015 United Nations Climate Change Conference (COP21), Intended Nationally Determined Contributions (INDCs) formed the basis of countries' early climate pledges. Upon ratification of the Paris Agreement, these INDCs transitioned into formal NDCs. To date, the NDC process has progressed through three rounds of target submissions, each expected to reflect increased ambition over time. Figure 6 illustrates the evolution of these NDC rounds and various key attributes.

There is increasing volatility of climate diplomacy and mounting geopolitical tensions, but the physical science around



Source: Daily Mail, adapted from Copernicus Climate Change Service (C3S), ECMWF and global temperature datasets (2024).
Graph shows annual average temperature increases from 1967 to 2024.

Figure 6: Global Surface Temperature Increases Above Pre-Industrial Levels, Showing Annual Averages From 1967 to 2024.

climate change is unambiguous and cannot be negotiated. Carbon dioxide (CO_2) is accumulating in the atmosphere at a faster rate than at any point in human history. 2024 marked the hottest calendar year on record (Figure 6), the first in which average global temperatures exceeded the critical 1.5°C threshold above pre-industrial levels. Without more ambitious NDCs, the 1.5°C target will be out of reach as current emission trends point to increasingly dangerous levels of warming.

Why Does Social Equity Matters in Energy Transitions?

Countries must integrate energy justice into their NDCs which must reflect energy justice across nations to ensure a just transition toward a flourishing life for all no one being left behind in a healthy planet–while protecting workers and communities affected by decarbonisation. Aligning energy justice with policy includes integrating equity into NDCs and linking access goals with climate strategies. A just energy transition should ensure that social equity is incorporated into and across NDCs that should be implemented in an inclusive, just, and sustainable.

Energy transitions, while essential for climate mitigation, can exacerbate social and economic inequalities across and within nations if not properly managed. The risks of mismanaging the transition to clean energy include job losses in traditional energy sectors, unequal access to clean energy technologies, rising energy costs for low-income households, and displacement from infrastructure projects.

Dimensions of Equity in NDCs

Embedding equity into and across NDCs ensures that the transition is not only green but also fair and just. The following dimensions should be considered when incorporating equity into NDCs:

- **Distributive equity:** ensuring fair allocation of costs and benefits
- **Procedural equity:** including marginalised voices in planning and implementation
- **Recognition equity:** acknowledging cultural, historical, and socioeconomic contexts

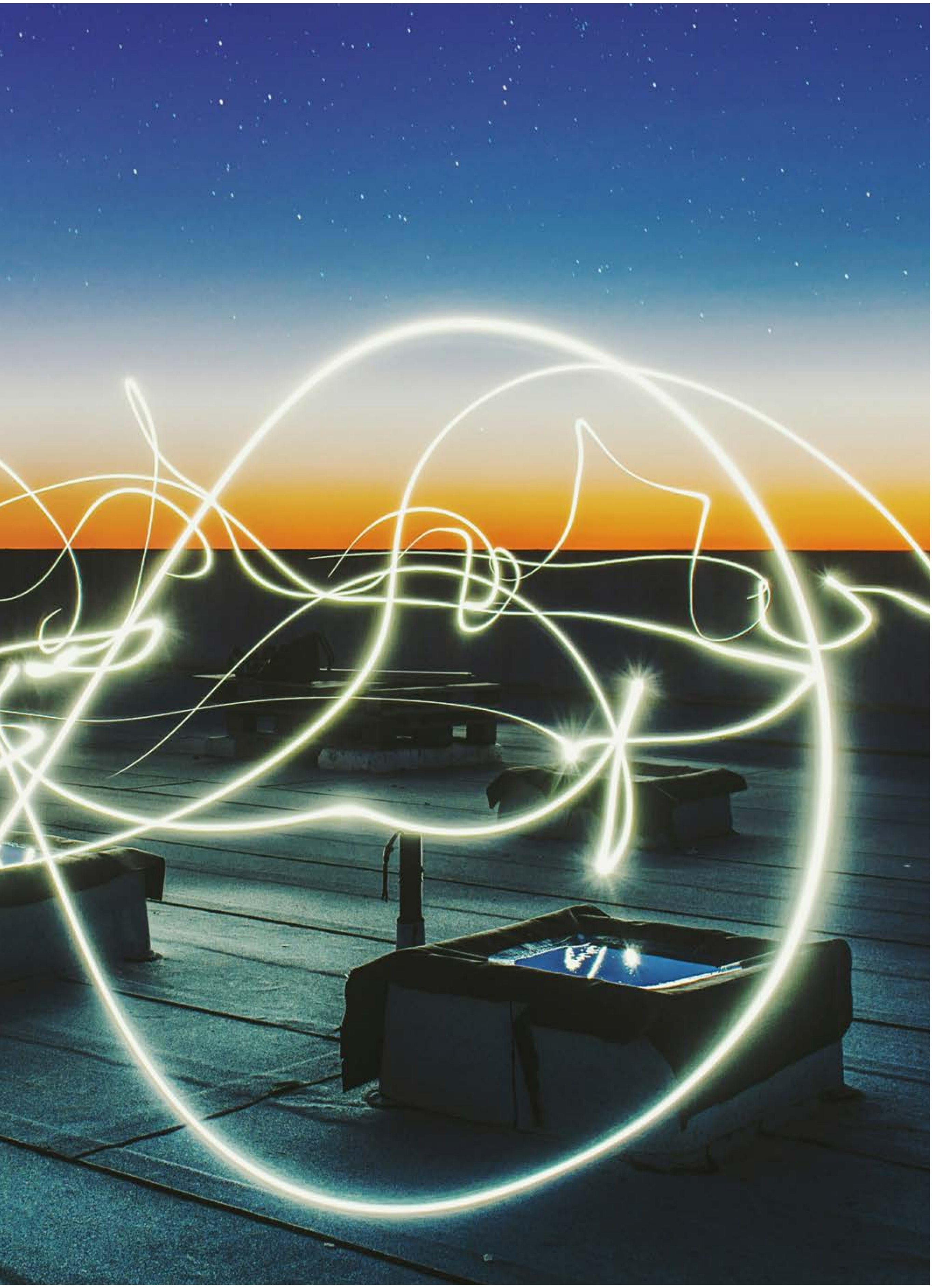
These principles, which countries can adopt to integrate equity into NDCs, are aligned with energy justice and SDGs, especially when incorporated with tools and instruments that strengthen accountability and transparency, such as:

- Equity assessments and social impact analyses
- Participatory governance in NDC planning and reviews
- Indicators and metrics to monitor gender, poverty, and livelihood impacts
- Budgeting and finance strategies targeting vulnerable groups

Conclusion

Energy justice provides a vital framework for ethical and equitable energy transitions. By focusing on access, affordability, and fairness, it helps ensure that the benefits of clean energy systems are distributed justly and inclusively across and within nations. Such a framework should recognise that reducing energy intensity is critical for sustainable development in emerging and developing economies. In this context, strategic policy frameworks, international collaboration, and technological innovation can help decouple growth from environmental degradation, while addressing any challenges that may persist.

As countries refine and implement their NDCs, integrating social equity should not be seen as optional, but essential for a sustainable and just energy transition. Future NDCs should be assessed not only by their climate ambition but also by their fairness across nations and their commitment to fairness, inclusivity, and human rights within nations.

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CHAPTER 10

THE GLOBAL SOUTH PERSPECTIVE – ENERGY TRANSITION IN DEVELOPING ECONOMIES

This chapter examines the contrasting manifestations of energy poverty in the Global North and Global South, while delving into the multifaceted challenges of the energy transition in developing economies. It highlights the interconnected issues of energy poverty, inadequate infrastructure, and limited access to climate finance that continue to impede progress in the Global South. Despite these barriers, innovative and context-specific strategies have emerged in countries such as Bangladesh, Kenya, and Uruguay, illustrating the potential to bypass traditional fossil fuel-based development through clean energy alternatives in Southeast Asia, Sub-Saharan Africa, and South America.

Bangladesh's large-scale deployment of Solar Home Systems, Kenya's off-grid solar expansion enabled by mobile money platforms, and Uruguay's swift transition to wind-powered electricity exemplify successful models of energy transformation. These case studies demonstrate that well-designed policies, inclusive governance frameworks, and strategic international cooperation can effectively harmonise economic development with climate goals.

The chapter emphasises that a just energy transition demands more than financial investments and technological innovation; it requires a socially inclusive and equitable approach that leverages local knowledge and prioritises support for vulnerable populations who must contribute to and benefit from the energy transition. This chapter also explores the multifaceted dynamics of energy transitions in the Global South through four interrelated lenses – the persistent challenges of energy poverty and financing, successful leapfrogging experiences, the role of international cooperation, and the just energy transition framework. By focusing on empirical case studies and up-to-date global data, the chapter aims to provide evidence-based insights for policymakers, researchers, and international stakeholders.

Understanding Energy Poverty: Divergent Realities in the Global North and Global South

Energy poverty, while a globally recognised issue, manifests differently across the Global North and Global South, reflecting underlying disparities in infrastructure, economic development, governance, and energy access. The concept, often simplified as a lack of access to modern energy services, encompasses broader socioeconomic, political, and cultural dimensions that are unevenly distributed between high-income and low-income regions.

In the Global North, energy poverty is generally framed in terms of affordability and efficiency. Households are considered energy poor when they spend a disproportionate share of income on energy or live in homes with inadequate heating or insulation. This is often linked to "fuel poverty," where people are unable to afford sufficient heating in winter, with health and well-being implications, especially for vulnerable populations.

By contrast, in the Global South, energy poverty is more acutely associated with the complete absence of electricity or reliance on traditional biomass (wood, dung, charcoal) for cooking and lighting. Thus, energy poverty in the Global South is more about absolute access than relative deprivation.

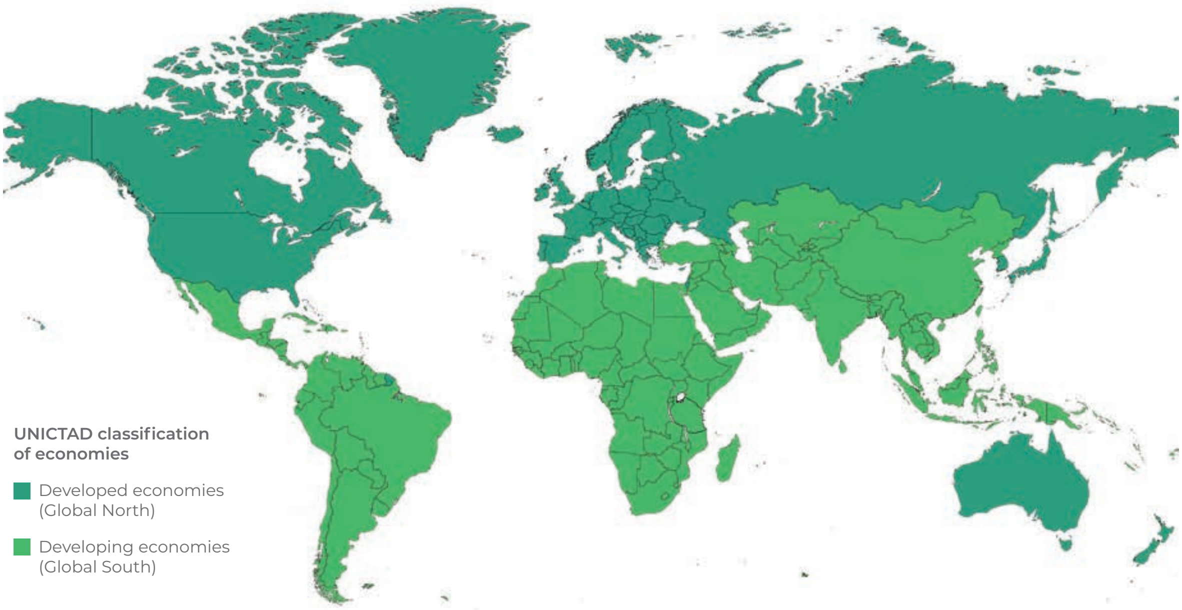


Figure 1: Global South Is Not a Univocal Geographical Definition, According to United Nations Conference on Trade and Development (UNCTAD) 2023, It Comprises Light Green Countries in the Map above. (Source: Wikipedia 2023)

These disparities are rooted in colonial histories, uneven development trajectories, and global financial architectures that have marginalised energy infrastructure investments in the South. Energy poverty here is "systemic and chronic," affecting not only households but entire regions and economic sectors, perpetuating underdevelopment and social inequality.

Energy poverty generates a cascade of interlinked problems. In the Global South, the most fundamental of those is the reinforcement and perpetration of poverty itself. In the Global North, while energy poverty does not typically threaten survival, it exacerbates social exclusion and undermines the quality of life. With the rising cost of energy and inflationary pressures, especially post-COVID and amid geopolitical shocks (e.g., the war in Ukraine and the Middle East conflicts and tensions), energy insecurity has once again become a primary political issue for both Global South and Global North.

Structural Challenges and Policy Gaps

A significant difference lies in the structural capacity to address energy poverty. The Global North generally has stronger institutional frameworks, financial mechanisms, and technological capabilities to mitigate energy poverty through subsidies, energy efficiency programmes, and targeted social protection. However, in the Global South, limited fiscal space, weak governance, and dependence on external aid or investment constrain the implementation of scalable solutions. Furthermore, dominant international development models have often imposed top-down, technocratic approaches that fail to account for local realities or empower communities. As Professor Stefan Bouzarovski notes, energy interventions in the Global South frequently overlook the social and cultural dimensions of energy use, leading to unsustainable outcomes.

Energy poverty is not a uniform challenge. It is shaped by intersecting inequalities and must be addressed through context-sensitive, multidimensional strategies. For the Global South, overcoming energy poverty is both a moral imperative and a prerequisite for achieving the Sustainable Development Goals.

The Dual Challenge: Navigating Energy Poverty and Emissions in the Global South

The global imperative for a modern energy transition, shifting from fossil fuels to low-carbon, renewable sources, has reached a critical juncture. Nowhere is this shift more urgent, yet complex, than in the developing economies of the Global South. These nations face a dual challenge:

1) Ensuring universal access to modern energy services while
2) Participating in the global effort to mitigate climate change and specifically the emissions of GHG

This task is complex, as energy access and emissions patterns vary widely across regions and even between countries in the same area. For example, China's total CO_2 emissions exceeded those of the advanced economies combined in 2020, and in 2023 were 15% higher. India surpassed the European Union to become the third largest source of global emissions in 2023.

Countries in developing Asia now account for around half of global emissions, up from around two-fifths in 2015 and around

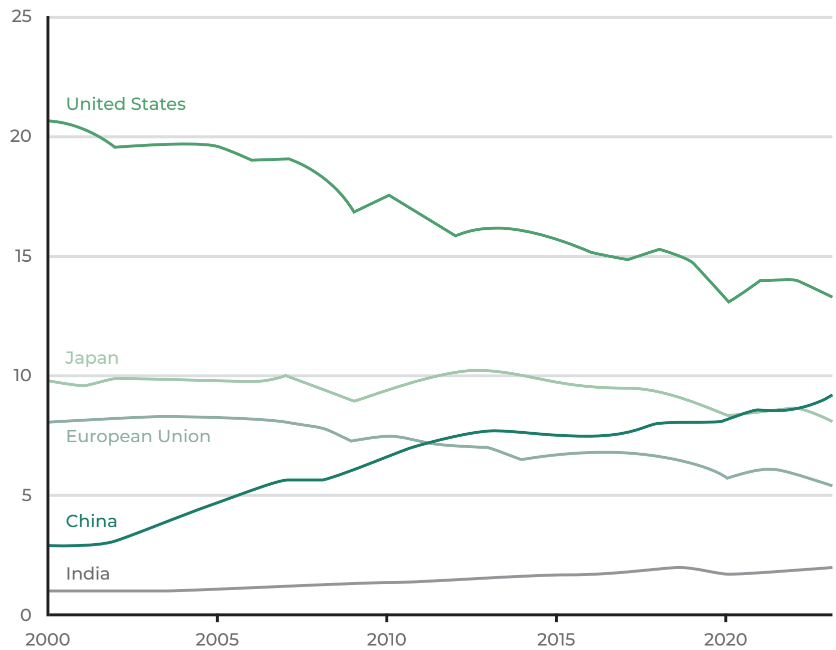


Figure 2: CO_2 Emission per Capita in Various Regions in Tons. (Source: International Energy Agency (IEA), 2023. Global Energy Review: CO_2 Emissions in 2023)

one-quarter in 2000. China alone accounts for 35% of global CO_2 emissions.

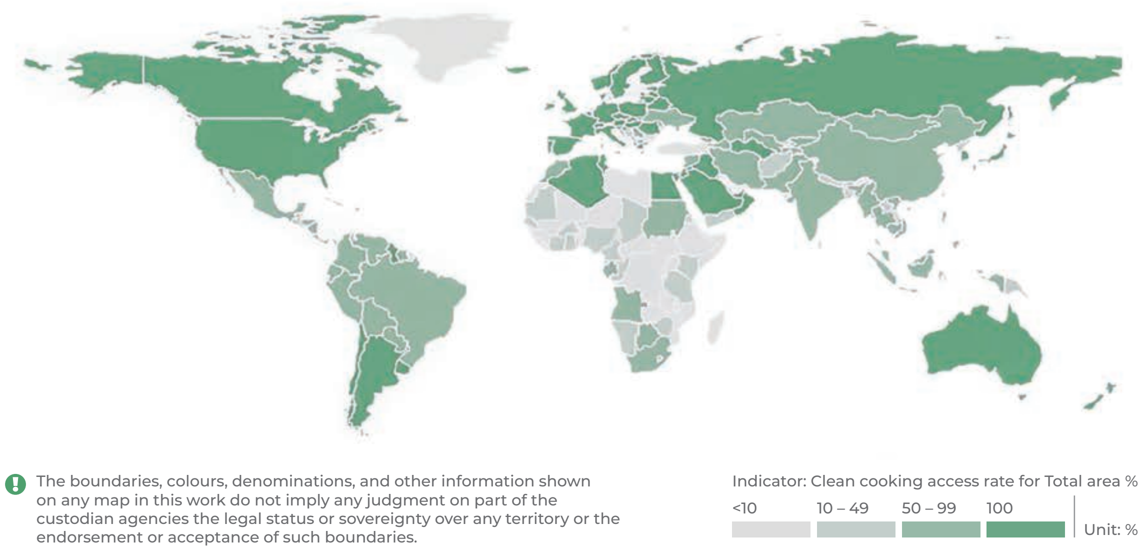
However, advanced economies continue to have relatively high per capita emissions, at about 70% higher than the global average in 2023. India's per capita emissions remain less than half of the global average, at around 2 tons. Per capita emissions in the European Union (EU) have fallen strongly and are now only around 15% higher than the global average and around 40% below those of China. China's per capita emissions exceeded those of the advanced economies as a group in 2020 and are now 15% higher; 2023 represented the first time that they surpassed those of Japan, although they remain one-third lower than those of the United States.

Conversely, energy poverty remains one of the most pressing global development challenges, defined by the lack of access to modern energy services such as reliable electricity and clean cooking fuels. As of 2022, an estimated 685 million people, predominantly in Sub-Saharan Africa (570 million) and South Asia, still lacked electricity access, while 2.1 billion relied on polluting cooking methods like biomass and kerosene.

Understanding Energy Poverty in the Global South

The above data presents an alarming picture regarding the achievement of the Sustainable Development Goal 7 (SDG 7) set by the United Nations. This is one of 17 Sustainable Development Goals established by the United Nations General Assembly in 2015. It aims to "Ensure access to affordable, reliable, sustainable and modern energy for the entire world by 2030". It recognises the access to energy as an important pillar for the wellbeing of the people as well as for economic development and poverty alleviation. The deprivation of reliable and clean sources of energy contributes to multidimensional socio-economic crises: children are forced to study by kerosene lamps, healthcare services operate without essential refrigeration, and small businesses struggle due to erratic power supplies.

The immediate effects of similar deprivations deeply affect the health of citizens of the Global South. The World Health Organization (WHO) reports that roughly 3.2 million people die annually from exposure to indoor air pollution caused by polluting fuels and technologies. The health burden is especially severe for women and children, who are often most exposed to indoor smoke. Moreover, the burden of gathering fuel, estimated at up to 40 hours per week, falls disproportionately on women,



World Health Organization. Population data based on the 2018 Review of World Urbanization Prospects.

Figure 3: Population With Access to Clean Cooking Fuels and Technologies (Global results 2022). (Source: World Bank, 2023 Tracking SDG7)

hindering their education and economic participation.

Moreover, geographically, rural populations account for 80% of the electricity access deficit, necessitating tailored off-grid solutions. As stated in the preamble, energy poverty in rural areas is "systemic and chronic" perpetrating a vicious cycle. Too often, smallholder plots of farmland yield just enough for a family to get by. These farmers face persistent risks of severe setbacks. Without electricity, lack of rain can kill crops or can rot the yields in case of floods, exposing them to persistent food insecurity and malnutrition. Without electricity, machinery, medical care, and other elements of modernity, there is little chance of a better future and life improvement.

The Persisting Gap

Despite some progress, the global trajectory toward achieving SDG 7 is significantly off-track. The 2023 edition of the Tracking SDG 7 report by the World Bank indicates that at current rates, 660 million people will remain without electricity and 1.8 billion without clean cooking solutions by the end of the decade.

While global electricity access rose from 84% in 2010 to 91% in 2021, (representing over one billion people newly connected), the pace of progress has slowed markedly since 2019. On one hand, rural electrification, particularly in South Asia, has contributed positively, with the region achieving a 95.8% access rate by 2020 through hybrid grid-renewable systems. In fact, access deficits in rural areas shrank from 886 million globally in 2010 to 562 million in 2022. The steepest decline was in Central and Southern Asia (from 383 million to "just" 24 million disconnected). By contrast, the deficit grew in rural areas of Sub-Saharan Africa (from 376 million to 473million).

In recent years, external shocks such as pandemics, wars and political instability have exacerbated the situation. As we saw in the preamble of this chapter, those shocks affected both the Global North and the Global South. Despite this, in the latter the effects were more acute due to the structural weakness of the energy system. The

INDICATOR	2015	LATEST YEAR
7.1.1 Proportion of population with access to electricity	**957.5 million** people without access to electricity	**685 million** people without access to electricity (2022)
7.1.2 Proportion of population with primary reliance on clean fuels and technology for cooking	**2.7 billion** people without access to clean cooking	**2.1 billion** people without access to clean cooking (2022)
7.2.1 Renewable energy share in total final energy consumption	**16.7%** share of total final energy consumption from renewables	**18.7%** share of total final energy consumption from renewables (2021)

Figure 4: Primary Indicators of Global Progress Towards the SDG 7 Targets (Source: World Bank, 2023 Tracking SDG7)

COVID-19 pandemic and the 2022 global energy crisis reversed years of gains in the Global South, leading to the first increase in global energy poverty since 2010. Rising fuel prices and mounting sovereign debt in developing countries have, in parallel, curtailed grid investments, increasing reliance on decentralised solutions such as Solar Home Systems (SHS) and mini grids.

However, in Global North economic recovery packages in the wake of the COVID-19 pandemic, and the global energy crisis caused by the wars in Ukraine and the Middle East, led many countries to strengthen policy support for renewables since 2022. Thanks to this, global renewable power registered a record year in 2023, almost 50% higher than 2022.

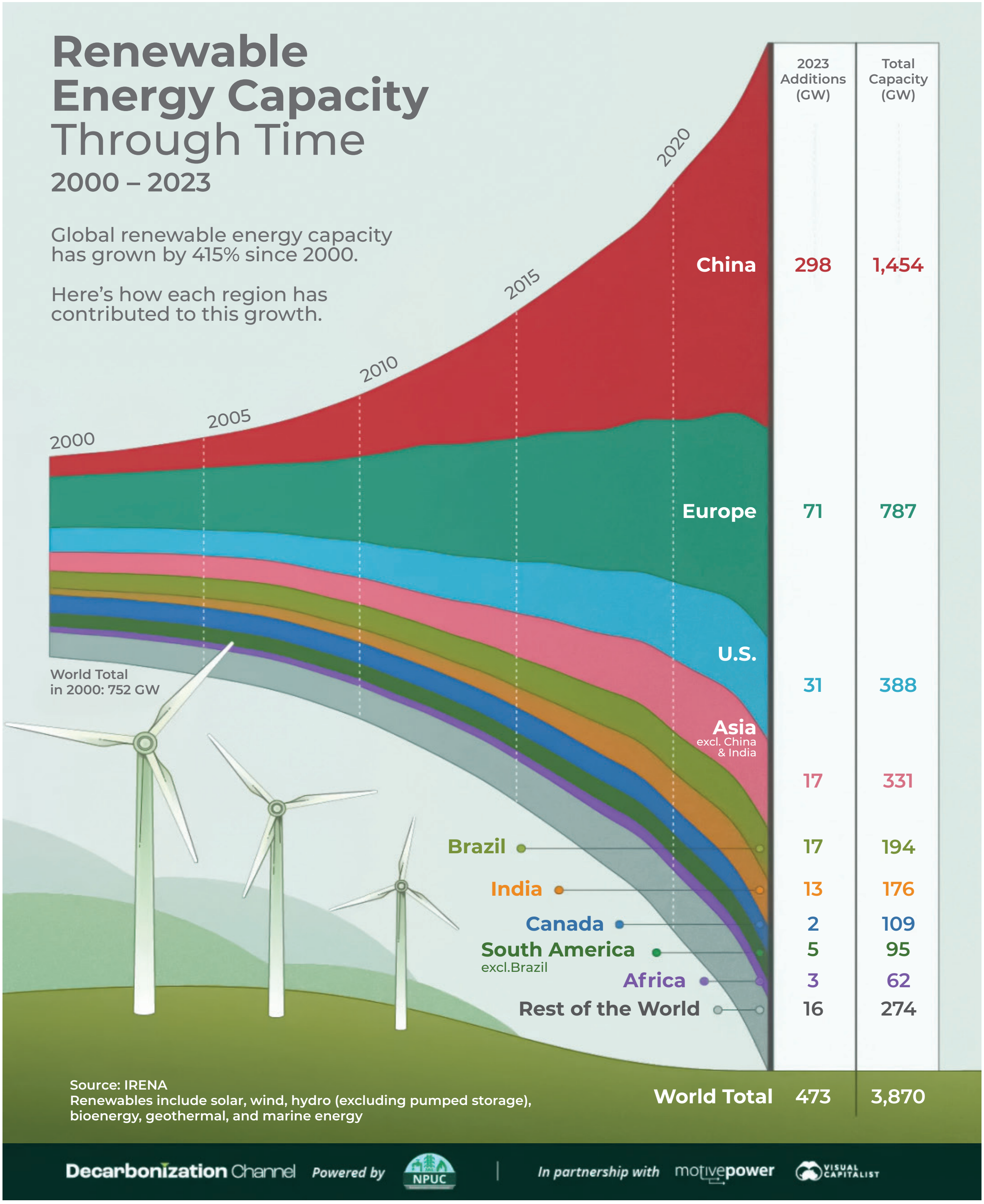


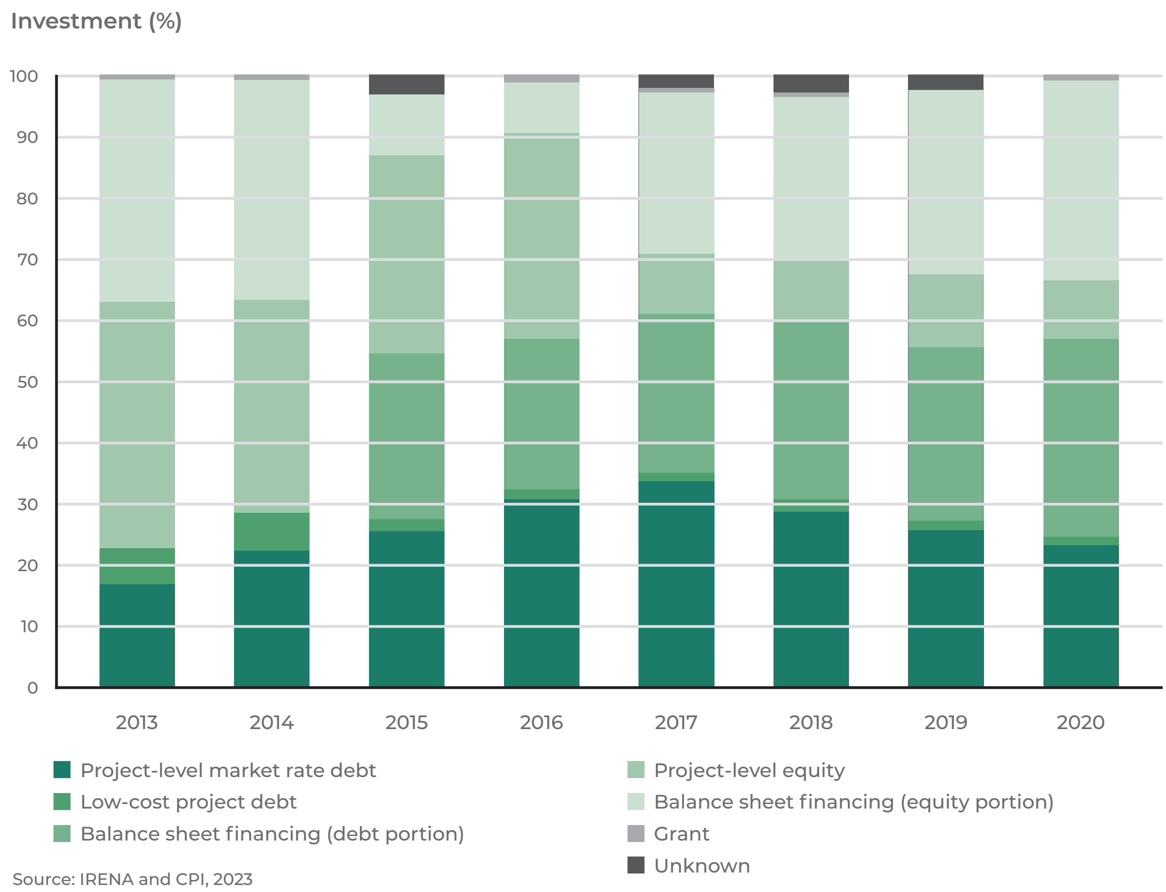
Figure 5: Visualised: Renewable Energy Capacity Through Time (2000–2023). Source: Decarbonisation Channel 2024

The Financing Issue

A key remains the decline in international public finance flows for clean energy in developing countries. G20 countries accounted for almost 90% of global renewable power capacity in 2023 with high investment from commercial financial institutions and corporations in Europe and North America. For developing countries, as of 2021, financial commitments stood at USD 10.8 billion, a 35% drop from the 2010-2019 average, and only 40% of the 2017 peak of USD 26.4 billion. Moreover, this funding was heavily concentrated: 19 countries received 80% of all international energy finance. IRENA has warned that public finance systems must be structurally reformed to unlock the investments required to close the energy access gap. In 2020, multilateral and bilateral Development Finance Institutions (DFIs) provided less than 3% of total renewable energy investments. Furthermore, since the interest rates applied are the same as market values, the only difference that DFI financing provides is to make finance available, but at high costs for users in Global South. This means that the lowest-income people pay the most, in relative terms, for renewable energy. Going forward, DFIs need to direct more funds, at better terms, towards large-scale energy transition projects. Also, financing from DFIs has been provided mainly through debt financing while grants and concessional loans amounted to just 1% of total renewable energy finance.

These institutions should act as the catalyst for finance easing as they are uniquely placed to support large-scale and cross-border projects that can make a notable difference in accelerating the global energy transition, especially in Global South countries.

Despite the above financing trend, there are reasons for cautious optimism thanks to the programme led by the World Bank and the African Development Bank (AfDB). Launched in April 2024, the so called "Mission 300" programme ambitiously aims to address energy poverty in Sub-Saharan Africa by expanding access to electricity to at least 300 million people in Africa by 2030. In parallel, South Asia's electrification rate



Source: IRENA and CPI, 2023

Figure 6: Global Investment in Renewable Energy by Financial Instrument, 2013-2020

reached 98.6% in 2023 partially through hybrid grid-renewable systems despite the population increase.

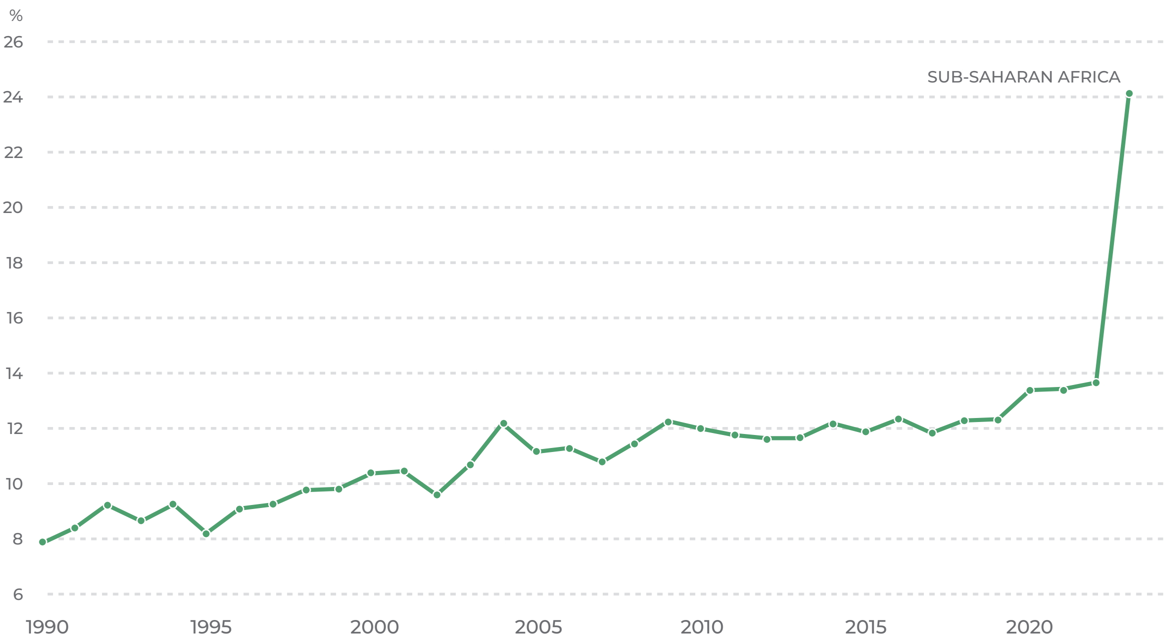
In Africa the World Bank is committed to connecting 250 million people, while the AfDB aimed to support an additional 50 million. This initiative focuses on leveraging distributed renewable energy systems, including SHS, to achieve its goals. For the World Bank Group to connect 250 million people, at least $30 billion of public sector investment will be needed. In addition, receiving governments will need to put in place policies to attract private investment, and reform their utilities so that those are financially sound and efficient with tariff mechanisms that protect the poor and do not subsidies energy generated through fossil fuels. It is expected that this pool of measures will act as a stimulus for substantial opportunities also for private investments in grid-connected renewable energy.

The Nexus: Lack of Adequate Financing-Poor Energy Infrastructure-Persistent Poverty

Energy infrastructure in much of the Global South remains underdeveloped, particularly in rural and peri-urban areas. Outdated transmission networks, limited grid coverage, and high distribution losses undermine efforts to deliver reliable energy access. According to the World Bank, technical and non-technical losses in Sub-Saharan African power sectors often exceed 20 percent, compared to a global average of around 6% in 2023. Most worryingly the two trends are opposite: The world grid gets better each year while the sub-Saharan one gets worse perpetrating the nexus: "lack of adequate financing-poor energy infrastructure-persistent poverty".

Furthermore, financing the energy transition remains a formidable challenge. In particular, energy investments in low- and

Electric power transmission and distribution losses (% of output) Sub-Sharan Africa



IEA Energy Statistics Data Browser, iea.org/data-and-statistics/data-tools/energy-statistics-data-browser
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Figure 7: Electric Power Transmission and Distribution Losses (% of output) - Sub-Saharan Africa. (Source: The World Bank 2023)

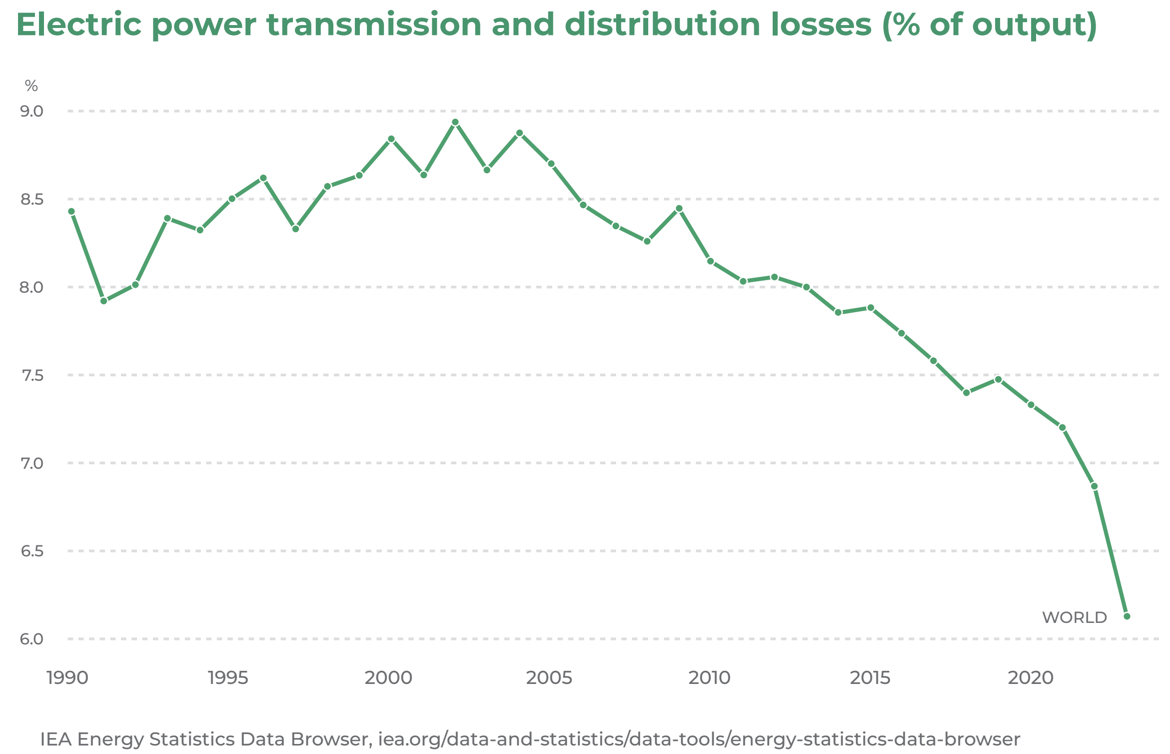


Figure 8: Electric Power Transmission and Distribution Losses (% of output). (Global Data.Source: The World Bank 2023)

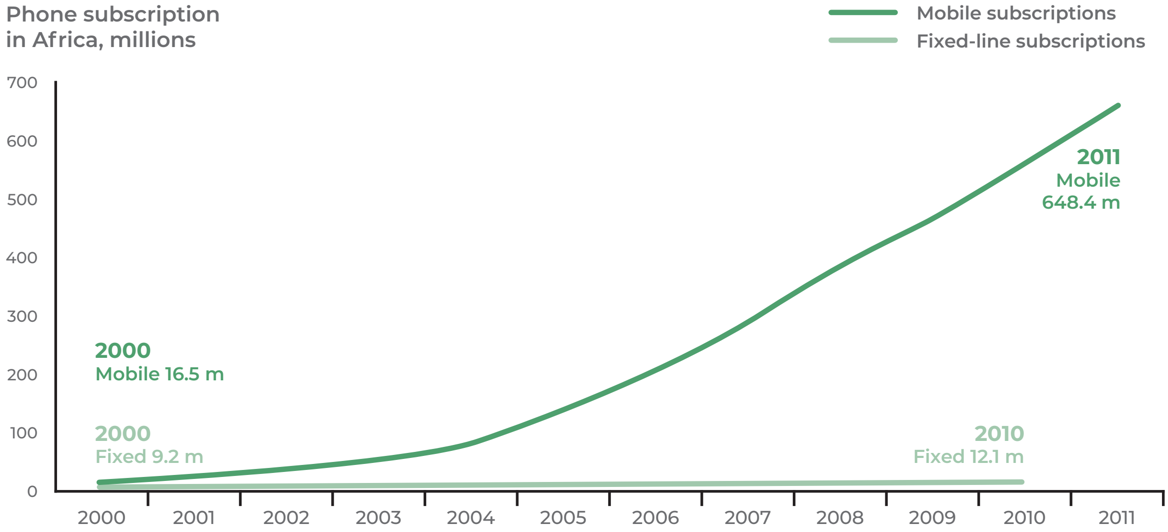
middle-income countries fall significantly short. Africa received only 2% of the USD 2.8 trillion (equivalent to USD 60 billion, excluding major hydropower) spent on renewables globally between 2000 and 2020. Moreover, three-fourths of the investments made in Africa during the same period were captured by just four countries: South Africa, Morocco, Egypt and Kenya. These countries offer relatively favourable risk-return profiles owing to their policy and institutional environments, regulations, access to finance and market characteristics such as size of the population, development prospects and political stability. Despite these few exceptions, all over the continent the private sector engagement is constrained by perceived risks, regulatory uncertainty, and currency volatility. Although concessional finance mechanisms — such as the Green Climate Fund and Climate Investment Funds — play a critical role, their disbursement processes are often slow, minimal, and poorly aligned with the urgent needs of the continent.

Leapfrogging Fossil Fuels: 3 Case Studies in Southeast Asia, Africa and Latin America

As we have seen in the previous pages, global energy transition poses a unique dilemma for the developing economies of the Global South. These nations are under mounting pressure to reduce greenhouse gas (GHG) emissions and contribute to the global decarbonisation agenda, while simultaneously striving to provide universal access to modern energy services and, hence, contribute to the enhancement of the living standards of their citizens. In contrast to the historical trajectory of industrialised countries, which relied heavily on fossil fuels during their development, many countries in the Global South face the imperative, and opportunity (if supported by the international institutions through-out, fit for purpose, finance tools), to "leapfrog" carbon-intensive pathways by adopting clean, decentralised, and technologically advanced energy systems from the outset. This dual challenge of achieving inclusive energy access and climate resilience has given rise to innovative models that integrate technological, financial, and policy frameworks tailored to local contexts.

Africa's mobile revolution

Mobile phone and fixed line subscription in Africa, 2000 – 2011.



Source: **World Bank, Wireless Intelligence and ITU.**

Figure 9: Mobile Phones and Fixed Line Subscriptions in Africa (2000- 2011)

Lessons from the Mobile Industry: A Precedent for Leapfrogging in Energy Access

Energy is not the unique case of Global South's leapfrogging in technologies. The telecommunications industry is another striking example (the first and the most investigated by academia, investors and policy makers in the early 2000s) of how developing regions can bypass expensive legacy infrastructure and adopt cutting-edge technology directly. Similar to electrification, in the early 2000s, fixed-line telephony penetration in sub-Saharan Africa was around 4-6%, among the lowest in the world, due to high infrastructure costs and logistical challenges in rural areas. Instead of investing in expensive landline networks, many African countries jumped straight to mobile cellular technology, which proved cheaper, faster to deploy, and more flexible.

By 2010, mobile phone subscriptions in Africa had skyrocketed from under 16 million in 2000 to over 500 million, representing a 3,000% increase in just a decade. Despite the parallel increase of the population, in 2023, roughly 89% of people in Sub-Saharan Africa have access to mobile phones, surpassing electricity access in some regions. This leap connected millions to mobile banking, internet services, and communication tools — catalysing economic growth, digital inclusion, and access to energy." in Kenya, the expansion of the energy sector closely followed the growth of the mobile telecommunications industry, particularly through the introduction of mobile phone-enabled pay-as-you-go (PAYG) financing models for sustainable energy technologies. Simultaneously, the increased availability of a reliable electricity supply facilitated the broader adoption and usage of mobile phones. The development of these two sectors progressed in parallel, with each benefiting from the advancements made in the other.

The above, coupled with the fact that mobile networks require far less physical infrastructure than landlines, (making them ideal for reaching remote and underserved populations), are some of the traits that are common in modern telecommunication and in the renewable electrification industries. Moreover, competition among mobile providers led to lower costs and rapid innovation. In summary, Africa's telecommunications leapfrogging has not only bridged the digital divide but also laid the foundation for similar advances in energy, health, and education sectors.

The Global South Decoupling Development from Emissions Growth

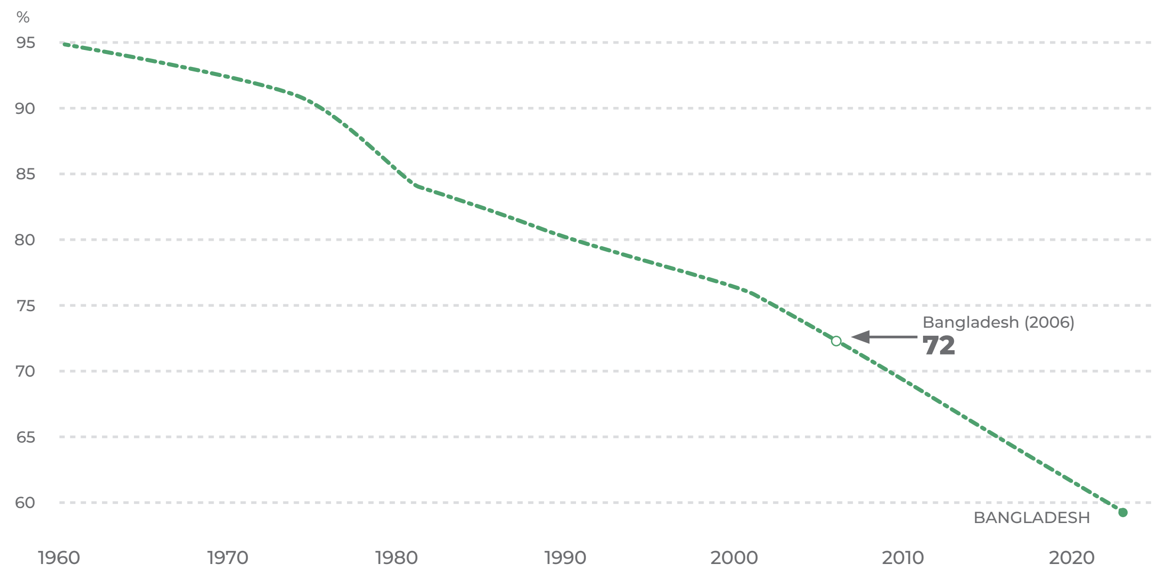
Going back to the electrification case studies, in the following pages we will examine three compelling case studies from Bangladesh, Kenya, and Uruguay, representing Southeast Asia, Africa, and Latin America respectively. Each case highlights how countries with limited initial energy infrastructure and significant socio-economic constraints have pioneered renewable energy strategies to bypass fossil fuel dependency. These examples are not only emblematic of what is possible with the right enabling environment but also offer scalable blueprints for other developing countries grappling with similar challenges.

In Bangladesh, the Solar Home Systems (SHS) programmehas revolutionised rural electrification by deploying millions of decentralised photovoltaic units, reaching households far beyond the national grid and dramatically improving quality of life. In Kenya, the proliferation of off-grid solar systems, led by innovative business models such as pay-as-you-go (PAYG), demonstrates how digital finance and entrepreneurship can expand clean energy access in underserved communities. Meanwhile, Uruguay stands as a rare example of a small nation that transitioned to a predominantly renewable electricity grid in under a decade, driven by public-private partnerships, targeted financial instruments, and ambitious policy frameworks. Together, these cases illustrate the diverse pathways through which countries in the Global South are decoupling development from emissions growth. They demonstrate that with political will, strategic investment, and inclusive design, energy transitions can simultaneously advance economic development, environmental sustainability, and energy justice. The subsequent sections delve into each case in detail, drawing out the policy mechanisms, financial models, and socio-economic impacts that have enabled these countries to leapfrog traditional fossil fuel paradigms.

Bangladesh's Solar Home Systems Revolution

Bangladesh provides a compelling illustration of how developing economies can bypass traditional fossil fuel dependency by adopting innovative, decentralised energy solutions. In 2006, still over 58% of the total population was not connected to the national unreliable electricity grid, the reason being the high costs to extend grid access to lowly populated areas. In the same year an estimated 72% of the entire

Rural population (% of total population) - Bangladesh



World Bank staff estimates based on the United Nations Populations Division's World Urbanization Prospects: 2018 Revision.
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Figure 10: Rural Population as % of the Total Population in Bangladesh in 2006

population still lived in rural areas without access to electricity, presenting a significant barrier to development and quality of life.

To address this challenge, the Government of Bangladesh, in partnership with the Infrastructure Development Company Limited (IDCOL, a state-owned infrastructure financing company, with technical and financial support from several development partners including the Asian Development Bank) and various international donors, initiated the Solar Home Systems (SHS) programmein 2003. The primary objective was to deploy small-scale solar photovoltaic (PV) systems in off-grid and remote areas where grid extension was either impractical or prohibitively expensive.

The SHS programme rapidly scaled up, and by 2018, over 4.1 million SHS units had been installed, providing electricity to approximately 20 million people, (about 14% of the country's population, 2011 Census). This initiative became the world's largest off-grid renewable energy programme, transforming rural energy access and living standards. Its success was underpinned by a combination of concessional financing, active private sector participation, and innovative consumer credit mechanisms, making solar technology affordable to low-income households. The SHS programme brought socio-economic benefits by providing households with reliable lighting — helping children study after dark and enabling businesses to operate longer. The programme also spurred local employment, with around 75,000 people directly or indirectly engaged in the SHS value chain. Furthermore, the widespread adoption of solar home systems reduced reliance on kerosene (saving consumption of circa 1.14 million tons), leading to significant cost savings-over USD 411 million and avoiding emissions of millions of tons of carbon dioxide (CO_2) over the systems' lifetimes.

Bangladesh's SHS model has become an international benchmark for decentralised renewable energy expansion in low-income settings. It demonstrates that targeted policy interventions, multilateral support, and an enabling business environment can catalyse large-scale progress in energy access, with far-reaching impacts on education, health, livelihoods, and environmental sustainability.

Kenya's Off-Grid Solar Revolution

Kenya has emerged as a continental leader in off-grid solar innovation, driven by a combination of entrepreneurial energy, supportive policies like the Kenya National Electrification Strategy (KNES), and technological advances. Kenya's off-grid solar revolution is exemplified by companies like M-PESA and M-KOPA, which pioneered the pay-as-you-go (PAYG) model for solar home systems (SHS). Similar companies, leveraged Kenya's widespread use of mobile money platforms, allowing rural households to make small, manageable payments for solar systems and appliances. Since its launch in 2011, M-KOPA has connected more than a million households in Sub-Saharan Africa to solar energy, providing not just lighting but also powering appliances like TVs and refrigerators, and even offering financial services such as health insurance and cash loans. This approach has made solar power accessible to low-income, off-grid communities that previously relied on expensive and polluting kerosene lamps.

The KNES strategy uses geospatial planning to identify cost-effective electrification options (mainly mini-grids and standalone solar systems) and recognises the crucial role of the private sector in delivering off-grid solutions to remote communities. KNES is part of a broader vision to transform Kenya into a newly industrialised, middle-income country by 2030, supporting the nation's "Big Four Agenda" of affordable housing, manufacturing, food security, and universal healthcare.

Kenya's commitment to off-grid solar is further demonstrated by other initiatives like the Kenya Off-grid Solar Access Project (KOSAP), launched in 2019 with World Bank funding. KOSAP targets 14 underserved counties, aiming to install 250,000 standalone solar home systems and 120 mini-grids by 2030, with a budget of $150 million. This project is expected to transform lives in remote regions by providing reliable electricity and modern cooking solutions, contributing to the government's goal of universal power access by 2030.

By 2018, through another similar regional initiative named "Lighting Africa" launched in Kenya in 2009 with the support of the World Bank and the International Finance Corporation (IFC), the country's rural

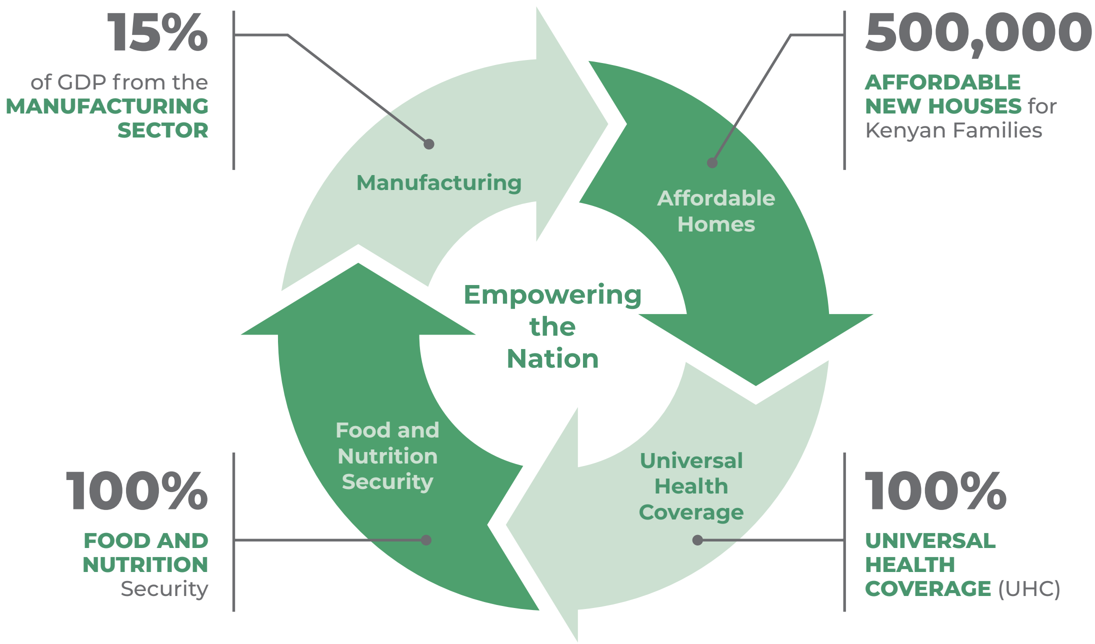
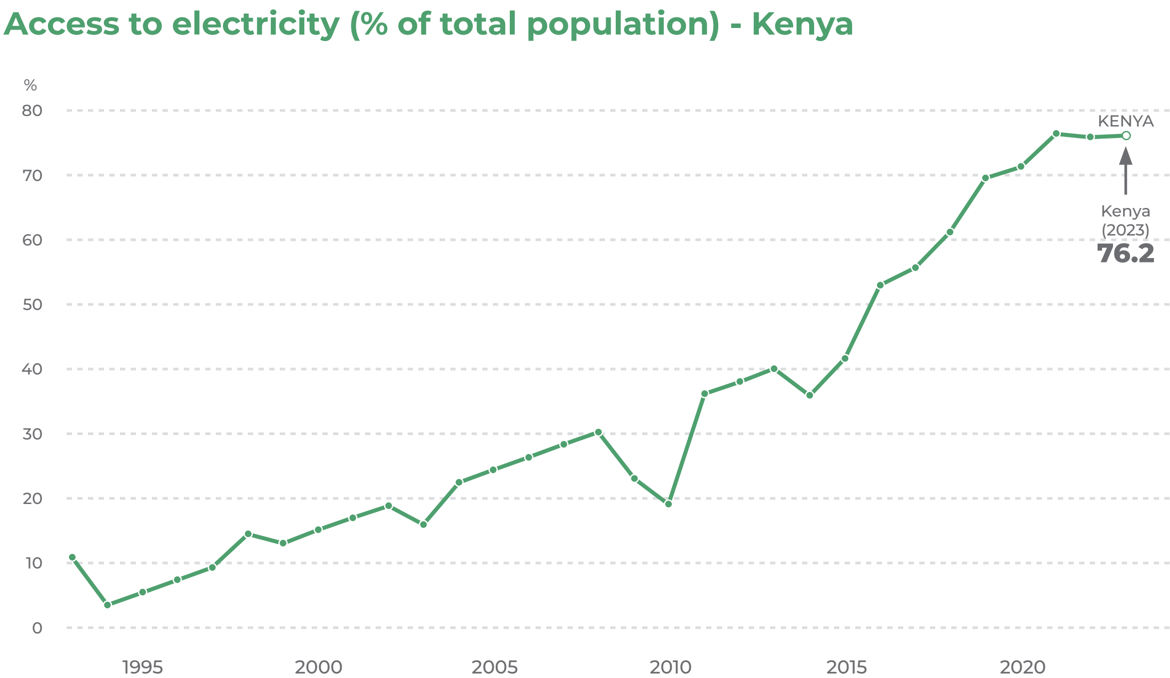


Figure 11: Kenya's "Big Four Agenda" (Source: Republic of Kenya (2018))

electrification rate reached 39.3%. An estimated 9.8 million Kenyans have benefited from this program, with the off-grid sector contributing significantly to rural electrification. The main lesson learned in the Kenyan efforts to reach 100% power accessibility by 2030 is that the PAYG model is particularly transformative, reducing the upfront cost barrier and enabling more families to afford clean energy. In essence it acts as a catalyst for electrification in rural areas. For example, M-KOPA's system typically requires a small deposit (around USD 35), followed by daily payments of about USD 0.45, less than what



IEA, IRENA, UNSD, World Bank, WHO. 2023. Tracking SDG 7: The Energy Progress Report. World Bank, Washington DC.

Figure 12: Access to Electricity as % of the Population in Kenya (1993 – 2023)

many families previously spent on kerosene. After about a year of payments, customers own their solar systems outright. This model has not only improved household lighting and reduced indoor air pollution but also enabled economic activities and improved education outcomes in rural areas. Kenya's off-grid solar revolution is a model for other countries, showing how international cooperation, innovative business models, digital payments, and enabling national policies can rapidly expand energy access, drive sustainable development, and improve living standards in rural communities.

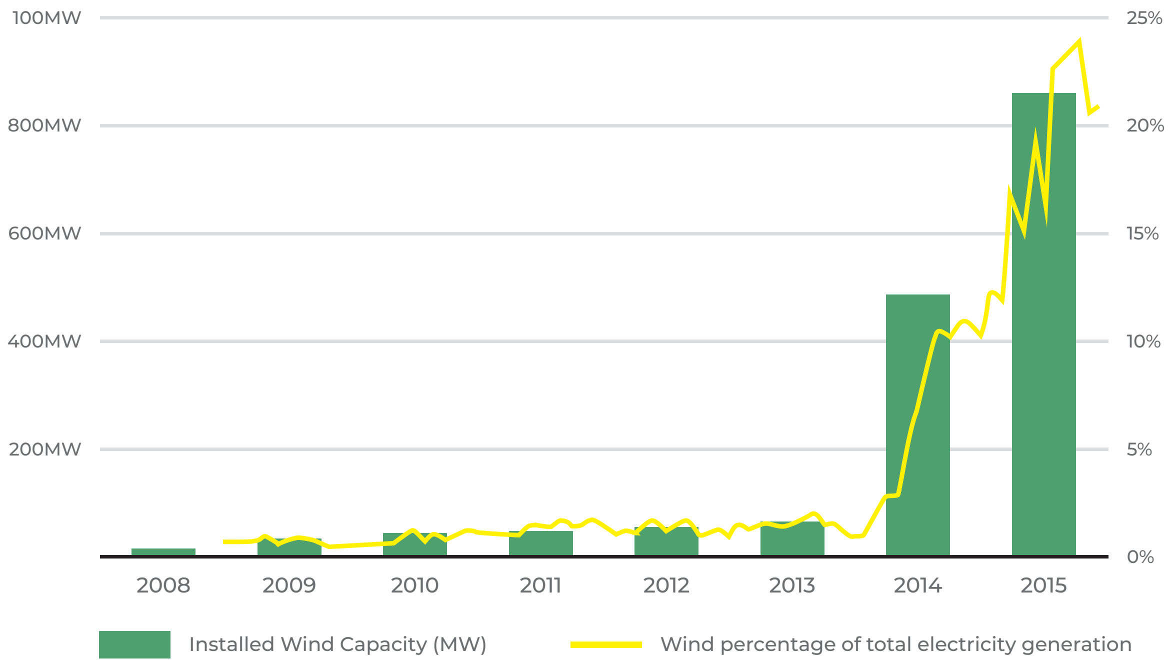
Uruguay's Wind Energy Transformation

Uruguay, a relatively small South American nation spanning 175,000 square kilometres (76,568 square miles) with a population of 3.4 million, 96% of whom live in urban centres, has achieved one of the most rapid and comprehensive renewable energy transitions globally, emerging as a benchmark for small nations pursuing energy independence through sustainable sources. Between 2008 and 2019, the country increased wind power's share of its electricity mix to nearly 34%, leveraging strategic policy frameworks, public-private partnerships, and targeted financial incentives. The progression did not stop: the amount of wind generated electricity in Uruguay in 2022 was 36.8%.

In parallel, the role of Uruguay has shifted from being an energy importer (34% of electricity demand in 2006 was supplied by neighbouring countries, primarily Argentina and Brazil) to a net energy exporter (10% of electricity generated locally in 2015 was exported).

This transformation was driven by Uruguay's urgent need to address energy insecurity caused by reliance on hydropower, which historically provided over 90% of electricity, but became vulnerable during the decade 1997 - 2007 due to prolonged droughts, and costly fossil fuel imports, which accounted for one-third of generation by 2007. In addition to import costs, the increased reliance on fossil fuels added to the fiscal burden of providing residential subsidies. Given

Uruguay's Wind Power Growth, 2008–2015



Source: MIEM, 2015. "Statistics," Montevideo, Uruguay: Ministerio de Industria, Energía Y Minería, Republic of Uruguay.

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Figure 13: Uruguay's Wind Power Growth (2008 – 2015)

the steadily rising electricity demand, the government sought ways to diversify its energy sources and use the public money differently. In the same year, the prompt and concrete response of the government was the launch of the Uruguay Wind Energy Program (initially spanning for 5 years till 2012), supported by a $1 million grant from the Global Environment Facility (GEF), delivered through the UN Development Program, and $6 million in national co-financing, to reform energy policies and build technical capacity.

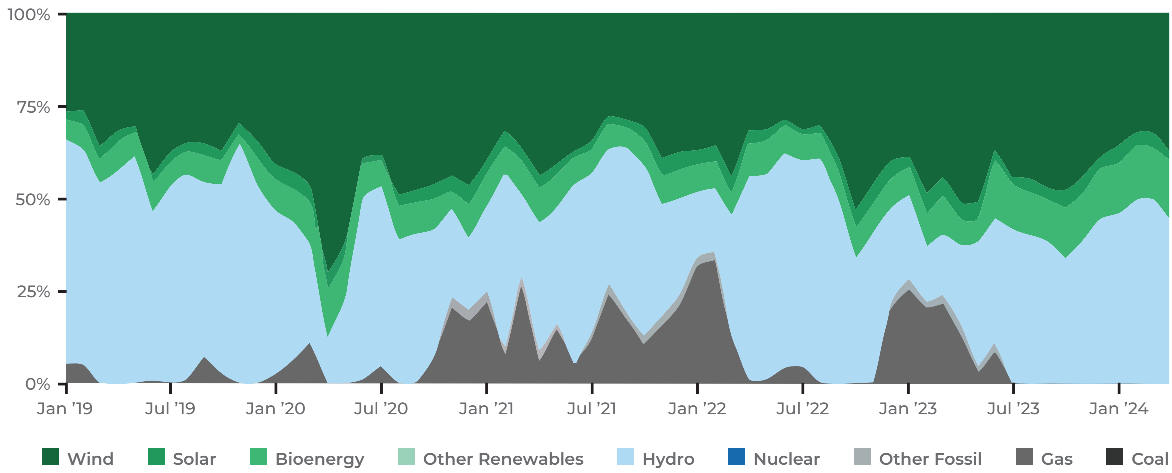
Key to this success was the adoption of competitive bidding mechanisms for large-scale renewables and feed-in tariffs for smaller projects, ensuring private producers could sell clean energy to the state-owned utility UTE at fixed prices for 20 years. These measures attracted private investment, enabling the installation of over 1,511 MW of wind capacity by 2018 (representing 31% of the country's installed capacity and the highest per capita globally at the time) and reducing electricity generation costs by stabilising long-term pricing.

Public-private partnerships played a pivotal role, with UTE guaranteeing power purchase agreements (PPAs) to de-risk investments, while requiring developers to employ local workers and strengthen grid infrastructure. By 2023, renewables, primarily hydro (42.9%), wind (40.6%), biomass (12.9%), and solar (3.5%), powered Uruguay's grid for 10 consecutive months, achieving near-total energy independence and avoiding volatile fossil fuel imports (in 2025, an astonishing 98% of the country's electricity comes from renewable sources).

> By 2018, Uruguay installed over 1,511 MW of wind capacity, representing 31% of national capacity — the highest per capita globally at the time.

Uruguay electricity generation by source

Percentage share



Source:Ember Electricity Data Explorer, ember-climate.org

Figure 14: Uruguay Electricity Generation by Source

The transition also delivered socio-economic benefits: electricity prices dropped significantly, power outages became rare, and approximately 50,000 jobs were created, representing 3% of the national workforce. Moreover, the government also used funding to train staff at the national electricity utility on how to work with renewable energy and created a renewable energy technology curriculum at Uruguay's *Universidad de la República* to train its staff. Uruguay's model demonstrates how coordinated policy, multilateral funding, and private sector collaboration can rapidly decarbonise energy systems while enhancing economic resilience.

Most importantly, it is worth noting that this energy transition has been developed without public subsidies. Instead, it has been based on auctions that allocate long-term contracts with the public utility. Simultaneously, innovative ways of financing projects have been developed; in the last few years Uruguayan citizens have been financing renewable energy projects through the local stock market in association with the public utility.

In conclusion, the experience of Uruguay's green transition over the past two decades demonstrates that there is no singular solution or "silver bullet" to achieving a successful energy transformation. Rather, Uruguay's progress has been the result of a convergence of multiple, interrelated factors, including:

- The characteristics of a small, cohesive and largely urbanised nation, which allowed for coordinated and efficient policy implementation
- A nation endowed with abundant hydropower, wind, solar, and biomass resources so far unexploited
- Close cooperation among the government, domestic financial institutions, academia, and the labour force, fostering a unified approach toward sustainable development
- A strong national resolve to reduce dependence on international fossil fuel markets, thereby mitigating the impact of global disruptions (such as wars, pandemics, or trade disturbances), over which Uruguay, as a small South American country, has little influence
- Targeted legislation that successfully encouraged private investment in renewable energy generation infrastructure, while maintaining public ownership and control over the distribution network through the state-owned utility UTE
- Public engagement in project financing, with citizens participating in the development of certain renewable energy initiatives through medium- to small-scale investment schemes

These combined elements underscore the importance of a multifaceted and inclusive strategy in realising a resilient and sustainable energy transition in Uruguay.

The Role of International Support

The energy transition in the Global South cannot be achieved without substantial international support and cooperation with the local players. This is based on three main pillars:

- Mobilising climate finance in a virtuous mix of private and public funding
- Enabling Technology Transfer
- Building institutional capacity

Global cooperation, particularly under frameworks such as the Paris Agreement, is essential to bridge existing gaps and ensure an equitable transition.

Climate Finance

Climate finance plays a pivotal role in enabling developing countries to pursue clean energy pathways. As of 31 December 2022, the Green Climate Fund (GCF), established under the United Nations Framework Convention on Climate Change (UNFCCC), had a portfolio of 209 projects and programs and an investment committed amounting to USD 11.4 billion toward initiatives that enhance climate resilience and low-emission development. Similarly, as of 31 December 2024, the Climate Investment Funds (CIF) collected from Global North donors roughly USD 12.5 billion to support renewable energy, energy access, and resilience initiatives globally.

However, the current flow of climate finance remains insufficient compared to needs. The UN estimates that developing economies require at least USD 1 trillion annually by 2030 to meet net-zero targets. Challenges include complicated and lengthy access procedures, high transaction costs, and limited alignment with national priorities.

Technology Transfer and Capacity Building

Technology transfer is crucial to enable the deployment of advanced clean energy systems across the Global South. Cooperation tools like the UNFCCC Technology Mechanism and initiatives under Mission Innovation seek to facilitate global technology sharing. Yet, barriers persist, including intellectual property restrictions, lack of technical expertise in vast areas of the globe, and adaptation challenges to the local environment. As demonstrated in the three case studies discussed above, there is not a single recipe that is applicable everywhere. Nevertheless, the successful adoption of innovative green technologies, in low-income countries, necessitates in all countries the direct or indirect involvement of the local workforce. Furthermore, it is advisable to establish close cooperation with local manufacturers (if any), developers, and educational institutions, such as technical schools and universities, in order to build a network of local technicians and subject matter experts capable of supporting the projects beyond the initial implementation phase. capacity building complements technology transfer by strengthening institutional, regulatory, and human capacities. Successful examples include technical training programs sponsored by the International Renewable Energy Agency (IRENA) and bilateral partnerships through organisations like GIZ.

Regional and Multilateral Cooperation

Regional cooperation is increasingly recognised as key to energy transition efforts. Initiatives such as the African Continental Power Systems Master Plan aim to coordinate electricity infrastructure across African nations. Similarly, in Southeast Asia, the ASEAN Plan of Action for Energy Cooperation (APAEC) outlines strategies for cross-border renewable energy trade and development. As we have seen in the examples of Bangladesh, Kenya and Uruguay, multilateral development banks (MDBs) like the World Bank, Asian Development Bank (ADB), and African Development Bank (AfDB) are instrumental financiers and facilitators of regional energy initiatives. Going forward, scaling up such cooperation remains crucial for collective progress.

Conclusion

The energy transition in the Global South is not only an environmental or technical challenge; it is a developmental imperative. With the right mix of financing, technology, innovative cooperative approaches, innovative business models and inclusive policy frameworks, developing countries can leapfrog carbon-intensive models and achieve sustainable growth. The success stories of Bangladesh, Kenya, and Uruguay highlight the potential for scalable, just, and locally driven transitions. As the world confronts the planetary climate emergency, enabling a just energy transition in the Global South is both a moral obligation and a strategic priority for global sustainability.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CHAPTER 11

ENERGY EFFICIENCY – THE GROWING PROMINENCE IN CLIMATE CHANGE MITIGATION STRATEGIES

Over the past decade, the urgency to mitigate climate change has intensified, placing the energy sector at the centre of global efforts to decarbonise. As countries strive to achieve energy security, economic development, and environmental sustainability — the so-called “energy trilemma” — the imperative to reduce greenhouse gas (GHG) emissions while ensuring reliable and affordable energy has never been more pronounced. Within this evolving policy landscape, energy efficiency has emerged as a strategic pillar, offering a cost-effective and rapidly deployable pathway to restrain energy demand growth, reduce emissions, enhance energy system resilience, and foster economic productivity. ▸

From energy efficiency to manufacture a product to energy efficiency to satisfy a human need

Energy efficiency improvement should be broadly understood as minimising the amount of energy required to satisfy a human need. This goes beyond reducing the amount of energy required for manufacturing products or producing services. It includes enhancing the lifetime and increasing the efficiency during use of energy intensive products and services.

Despite well-documented benefits of this systemic understanding of energy efficiency, it is not well known and remains significantly underutilised. Fragmented approaches to climate and sustainability actions, structural and behavioural barriers, insufficient availability of upfront financing, and fragmented policy frameworks have hindered their widespread adoption, particularly in developing countries. Nevertheless, growing recognition of its critical role in climate and development strategies is set to reshape the global energy discourse.

Energy efficiency – often described as the "first fuel" due to its potential to deliver energy services without additional energy supply – is increasingly being acknowledged as indispensable to achieving global climate goals. Efficiency measures, (i) lowering the amount of energy required to produce goods and services, or (ii) enhancing the lifetime of energy intensive products and/or (iii) increasing their efficiency at use reduce emissions at the source whilst also bringing co-benefits such as lower energy bills, reduced need for investment to replace an energy intensive product or need of less energy intensive products to satisfy a specific need, improved air quality, and enhanced industrial competitiveness.

In recognition of its centrality to the net-zero transition, the international community took a landmark step at the 28th United Nations Climate Change Conference (COP28) to the United Nations Framework Convention on Climate Change (UNFCCC) in 2023. There, countries agreed to collectively double the global average annual rate of energy efficiency improvements of products manufacturing from the historical average of around 2% to 4% every year until 2030. This target is intended to align global efforts with the Paris Agreement's ambition of limiting warming to 1.5°C.

The COP28 pledge has galvanised new momentum among policymakers, development institutions, and private sector actors, reinforcing the idea that energy efficiency is not only a technical fix but a strategic lever for achieving equitable and sustainable development. With governments currently preparing their next round of Nationally Determined Contributions (NDCs) under the Paris Agreement, there is an opportunity to ensure that ambitious energy efficiency measures for human needs satisfaction are a central to long-term national energy plans.

This chapter explores the multifaceted role of energy efficiency in the global energy transition, examining its conceptual frameworks, recent global and regional trends. It provides a sectoral analysis of energy efficiency measures in buildings, industry, and transport, and highlights how supportive policies, emerging technologies, and behavioural changes can unlock energy efficiency potential, being a driver of sustainable and low-carbon development.

Conceptual foundations and global momentum of energy efficiency

Energy efficiency refers to the ability to deliver the same or improved levels of energy services, such as heating, cooling, lighting, or mobility, while using less energy. It involves the implementation of technologies and practices that reduce energy input in an entire value chain without compromising performance or comfort. For instance, an energy-efficient building may achieve the same indoor temperature with significantly less heating or cooling demand, due to better insulation and smart control systems.

It is important to distinguish energy efficiency from energy conservation. While both aim to reduce energy consumption, conservation typically involves behavioural or lifestyle changes (e.g., reducing thermostat settings or limiting car use), whereas efficiency entails technological and systemic improvements that optimise energy use per unit of output or service. Thus, energy efficiency is generally framed as a means of decoupling energy consumption from economic growth, enabling countries to expand productive capacity and improve living standards while minimising energy demand increase. Energy efficiency is often measured by energy intensity—the energy required to produce a unit of economic output. This is a key global metric for tracking efficiency progress.

The conceptual origins of energy efficiency are closely linked to the geopolitical and economic turmoil of the 1970s. Prior to the first energy crisis in 1973, energy efficiency received little attention. Oil was cheap, and new discoveries reinforced confidence in a steady supply. However, the 1973 Arab oil embargo and sharp increase in the world oil prices exposed the vulnerability of oil-importing nations and triggered widespread concerns over energy security. This led to growing recognition that rising energy demand along with fossil fuel supply shortages would threaten economies built on the promise of cheap energy, and oil-importing countries would have to seek efficient use of energy

In response to the oil crises, many governments began implementing targeted measures. In the United States, between 1975 and 1978, the federal government established the first fuel economy standards for vehicles and introduced household appliance efficiency standards. It also launched the Weatherisation Assistance Program, aimed at improving energy efficiency in low-income homes through insulation and heating system upgrades, and introduced the first tax credits for energy-saving investments. In Japan, the government enacted the Energy Conservation Act in 1979 to promote energy-saving measures across all sectors and reduce total energy demand. Many European countries introduced building insulation requirements and launched public awareness campaigns. At the international level, the International Energy Agency (IEA) was established in 1974 by the Organisation for Economic Co-operation and Development (OECD) member countries to coordinate collective responses to oil supply disruptions, with energy efficiency among its early objectives.

This wave of actions was accompanied and reinforced by a new vision of energy thinking, with energy efficiency increasingly recognised as an energy resource rather than a marginal technical fix. Particularly, a pivotal theoretical contribution came from Amory B. Lovins, whose article "Energy Strategy: The Road Not Taken?" (1976) articulated a vision of a "soft energy path" predicated on the rapid development of renewable energy sources, transitional fossil-fuel technologies, and a commitment to the efficient use of energy. The key point of Lovins's argument was the development of the concept of energy efficiency: using less energy to produce more economic output. In this publication, he argued that technical improvements alone could double the amount of social benefit obtained from each unit of end-use energy in the next few decades, and suggested that by around 2000, efficiency could double with only minor or no changes in lifestyles, and that between 2010 and 2040, per capita energy use could fall to a third or a quarter of then-current levels. Soon after the publication of this paper, ideas about energy efficiency as a fuel began having an effect on government policies.

Improvements in efficiency were traditionally measured as the negative quantity of energy– an intangible gain compared to the more visible outputs of fossil fuel production or renewable energy generation. This invisibility led to energy efficiency being described as the "hidden fuel", valued primarily through its indirect effects, such as reduced energy demand and avoided energy costs. Consequently, targeted policies – such as appliance standards, building codes, industrial energy management, and efficiency programmes in electricity generation and distribution – began laying the groundwork for a larger role for energy efficiency.

Over time, a shift occurred as the contribution of energy efficiency to economic, environmental, and energy security goals became increasingly evident. This shift was institutionalised in the 2010s through the work of international organisations like the IEA, which began to frame energy efficiency as the "first fuel" – the most readily available, least-cost, and cleanest energy resource. The concept of energy efficiency as the "first fuel" emphasised its centrality to achieving sustainability targets. Energy efficiency also came to be described as a "low-hanging fruit", highlighting its cost-effectiveness, rapid deployability, and scalability relative to capital-intensive energy infrastructure.

Today, the framing of energy efficiency as a strategic energy resource is reinforced by compelling empirical evidence. For example, between 2010 and 2022, improvements in energy intensity were responsible for over 82% of the global reduction in energy-related CO_2 emissions This amounts to nearly 7 Gt CO_2, equivalent to almost the combined CO_2 emissions of the United States and India in 2022.

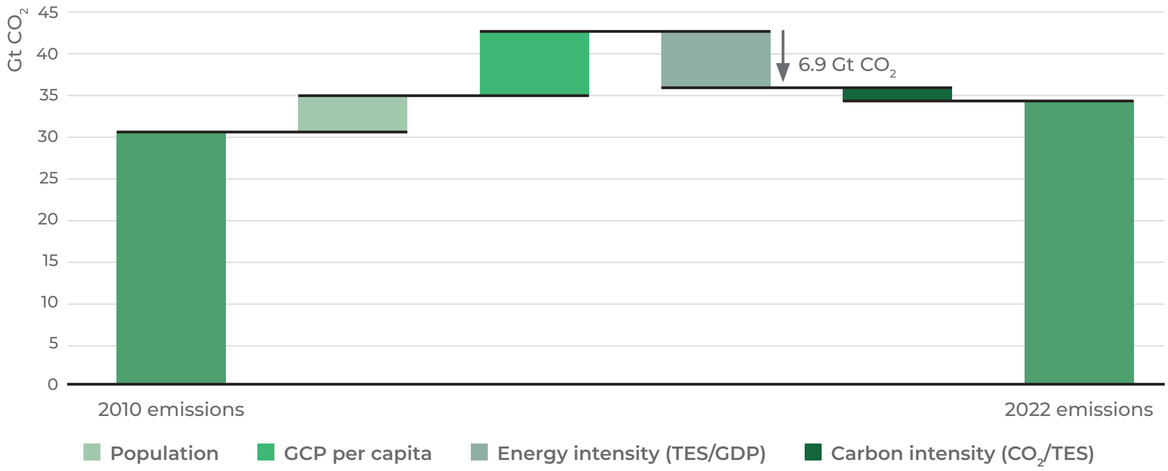


Figure 1: Contribution of Energy Intensity Improvements to the Reduction of Global CO_2 Emissions. (Source: IEA's Energy Efficiency, 2024)

For industry, efficiency upgrades often lead to improved process control, reduced maintenance needs, and enhanced competitiveness. At the household level, energy-efficient homes not only lower utility costs but also improve indoor thermal comfort and reduce exposure to indoor air pollutants, thereby enhancing public health. In cities, efficient public transport and building design contribute to cleaner air, reduced traffic congestion, and better urban liveability. Efficiency improvements also tend to create jobs, from construction work retrofitting buildings to innovation in efficient appliances and vehicles.

In developing countries, energy efficiency can expand access by stretching limited supply, reducing the need for costly infrastructure investment, and enhancing energy affordability for low-income populations. These co-benefits underline the role of energy efficiency as an enabler of sustainable development. Recognising and quantifying these benefits is essential for building strong economic and political cases for efficiency policies, particularly in resource-constrained settings.

At the international level, energy efficiency occupies a central position in climate and development agendas. It is prominently featured in countries' Nationally Determined Contributions (NDCs) and embedded within long-term decarbonisation strategies. Global collaborative efforts, including the IEA's Global Commission for Urgent Action on Energy Efficiency, the Clean Energy Ministerial, and the United Nations' Sustainable Energy for All (SEforALL) initiative, have been instrumental in disseminating best practices, mobilising finance, and building technical capacity across jurisdictions.

The most notable recent development was the agreement at COP28 in 2023 to double the global rate of efficiency improvement by 2030. This collective target – essentially aiming for 4% per year global energy intensity reduction – provides a clear benchmark for national plans. It builds on the earlier UN Sustainable Development Goal (SDG) 7.3 target and reflects a recognition that faster action is needed for climate goals.

Recent Global and Regional Trends in Energy Efficiency

Global trends

From 2010 to 2019, global energy efficiency recorded steady progress, with primary energy intensity improving at an average annual rate of around 2%. This trend was underpinned by a combination of technological advancements, structural economic changes, and targeted policy interventions. The retirement of inefficient industrial assets and the deployment of modern, lower-intensity technologies played a pivotal role, particularly in energy-intensive sectors such as steel and cement. Concurrently, the uptake of high-performance building technologies, including advanced insulation, energy management tools, and smart systems, helped mitigating strong energy demand growth in residential and commercial buildings. A global shift toward less energy-intensive industries, coupled with the rapid expansion of the services sector, further decoupled energy use from economic growth. Moreover, the widespread adoption of energy efficiency regulations, such as appliance performance standards and building codes, accelerated progress in many countries.

The COVID-19 pandemic disrupted this positive trajectory. Economic contractions in 2020, triggered by lockdowns and reduced industrial and transport activity, led global GDP to decline more sharply than energy consumption, resulting in only marginal improvements in energy intensity. In 2021, the rebound in global economic activity led to the largest single-year increase in energy demand in over five decades, with consumption rising by more than 5% as industry, mobility, and air travel resumed. Consequently, global primary energy intensity improved by just 0.5% in 2021, well below historical trends (Figure 2).

A partial recovery occurred in 2022. Skyrocketing fuel prices and heightened energy security concerns, triggered by the global energy crisis, catalysed urgent policy and consumer responses. Governments enacted emergency measures such as thermostat regulations and public campaigns, particularly in Europe. These interventions, combined with investment in efficiency upgrades, resulted in a 2% global improvement in energy intensity. This reaffirmed the role of energy efficiency as the "first fuel" – a rapid-response mechanism in times of crisis.

While the energy crisis marked a possible turning point for energy efficiency in some countries, global energy intensity progress has been lacklustre in 2023 and 2024. Key reasons for this slowdown include investment in manufacturing-intensive industries and economic recoveries in major emerging markets.

Despite a slowdown in global progressing recent years', the energy crisis has acted as a catalyst for accelerating both the energy transition and energy efficiency actions in

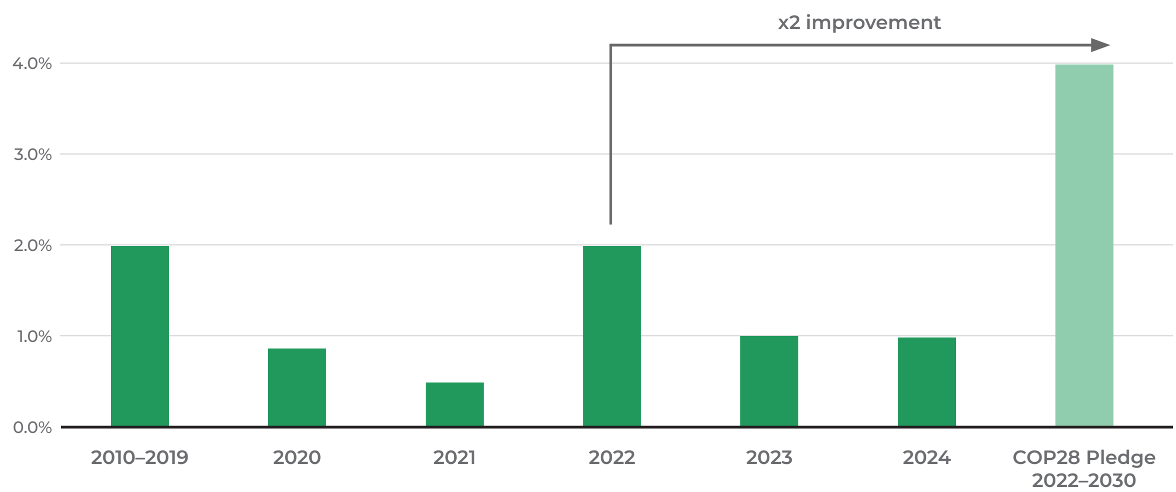


Figure 2: Primary Energy Intensity Improvement, 2010-2024, and COP 28 Pledge Target. (Source: IEA's Energy Efficiency Progress Tracker; IEA's Global Energy Review 2025)

many markets. Countries representing over 70% of global energy consumption have introduced new or significantly strengthened energy efficiency policies However, it is important to recognise that the impact of new policies is not immediate with improvements in energy intensity and efficiency typically unfolding over a period of years.

It is also worth mentioning that in 2024, combined public and private investment in energy efficiency across end-use sectors (buildings, transport, and industry), including investments in electrification such as electric vehicles or heat pumps, rose to approximately USD 660 billion. This marked a new record, surpassing the previous all-time high of USD 560 billion set in 2022. Since 2019, global investment in energy efficiency has grown by nearly 50%).

Regional Highlights

Behind the global averages, regional trends in energy efficiency reveal a diverse picture of progress and challenges. Differences in economic structure, levels of development, demographic patterns, climate conditions, and urbanisation rates mean that a uniform trajectory is unlikely. In advanced economies, where energy systems are already relatively efficient, the focus tends to be on incremental efficiency improvements and integrating digital technologies. In contrast, developing regions often face the dual challenge of expanding access to modern energy services while avoiding the lock-in of inefficient infrastructure.

North America recorded strong performance in 2022–2023, with the United States achieving a 3.5% improvement in primary energy intensity in 2023.

In recent years, some regions and countries have achieved unprecedented gains. In 2022 and 2023, the European Union (EU) emerged as a leader in energy efficiency gains, driven largely by its response to the acute energy crisis (Figure 2). A combination of emergency measures to curb gas and electricity consumption, elevated energy prices that incentivised savings, and an already robust policy framework contributed to this outcome. Long-standing regulatory instruments, such as stringent appliance, vehicle efficiency standards and support for low-carbon technologies, were reinforced by behavioural change campaigns and industrial optimisation efforts.

North America also recorded strong performance during 2022–2023, with the United States registering a 3.5% improvement in primary energy intensity in 2023. This was driven by widespread adoption of efficient technologies, bolstered by strengthened fuel economy standards and the extensive incentives under the 2022 Inflation Reduction Act (IRA). Revision of the IRA may reduce these gains as tax incentives are removed from its provisions! In the power sector, the ongoing shift from coal to natural gas and renewables also contributed to overall conversion efficiency.

China, the world's largest energy consumer, plays a pivotal role in shaping global efficiency trends. From 2010 to 2019, it achieved an average annual improvement of 3.8%, driven by Five-Year Plans targets, industrial restructuring, and major initiatives such as the Top-1000 Enterprises energy-saving programme.

However, China's energy efficiency progress has slowed in the early 2020s. In 2021 and 2022, the country's post-COVID-19 recovery was driven by a resurgence in energy-intensive industrial activity. In 2023, strong economic growth of around 5% led to a sharp increase in energy consumption, causing energy intensity to worsen as energy use grew faster than GDP. In 2024, energy efficiency improved modestly, with primary energy intensity declining by approximately 1.5%. To restore momentum, the 14th Five-Year Plan sets a target of reducing energy intensity by 13.5% between 2021 and 2025, aiming to put efficiency back on a steady upward trajectory.

The impact of energy-intensive industries on energy efficiency is specifically apparent in China, which is the world's manufacturing hub. It is estimated that the country uses 40% more energy to fuel GDP growth than the United States and almost double the energy to fuel the same economic growth than in the EU.

India recorded an estimated 2.5% improvement in primary energy intensity in 2024, aligning with its 2010–2019 average. India implemented a range of efficiency initiatives – from the Perform, Achieve, Trade (PAT) scheme that sets efficiency targets for large industries to massive LED bulb distribution under the UJALA programme and vehicle fuel economy standards. These efforts are gradually yielding results. While India remains the world's fastest-growing economy, energy demand growth has been tempered by policy-led efficiency gains, specifically as more people get access to much-needed cooling technologies and other appliances.

As shown in Figure 3, recent years have witnessed considerable variation in energy efficiency progress across regions and countries. Meanwhile, these disparities narrowed in 2024: improvements in energy intensity slowed in advanced economies, whereas progress in emerging and developing economies remained steady or slightly improved.

Against this backdrop, the landmark agreement at COP28 to double the global average annual rate of energy efficiency improvement by 2030 stands as a pivotal step toward achieving energy and climate goals. As Figure 2 highlights, two years on from this historic agreement, however, policy responses have yet to translate into faster efficiency progress. Meeting this target – equivalent to achieving a 4% annual reduction in global primary energy intensity – will require a scale-up in policy ambition, investment, and behavioural change.

Figure 3: Primary Energy Intensity and Annual Change by Region 2010-2024 (Source: IEA's Energy Efficiency Progress Tracker)

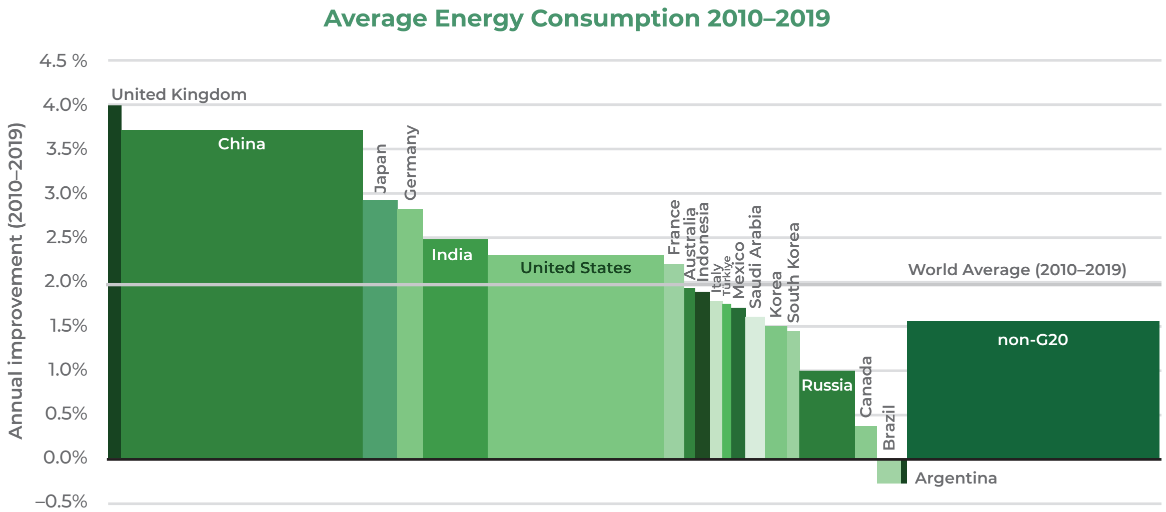


Figure 4: Average Energy Intensity Improvement, Selected Countries, 2010-2019. (Source: IEA's Energy Efficiency, 2024)

It can be also insightful to analyse what levels of energy intensity progress individual countries have reached over a sustained period. Among 150 countries assessed between 2010 and 2019, 91% achieved at least one year of 4% or higher improvement. Over half (52%) did so at least three times, only a few sustained this pace over extended periods. For instance, during the 2010s, among G20 countries, only one, the United Kingdom, achieved an average annual improvement of 4% across the entire decade (Figure 4).

Meanwhile, a subset of countries has demonstrated that such high levels of improvement can be sustained for shorter periods. For example, China, France, Indonesia achieved a 4% average improvement over a continuous five-year stretch. For the members of the G20 nations, whose progress contributes a greater weight toward the global target, 75% of countries exceeded 4% or came close with annual improvements above 3% at least once in every four years (Figure 5). Accordingly, the data provided suggests that doubling the global rate of energy intensity improvement this decade is challenging, but not unprecedented.

However, it is important to note that energy efficiency improvements exhibit two fundamental characteristics influencing their

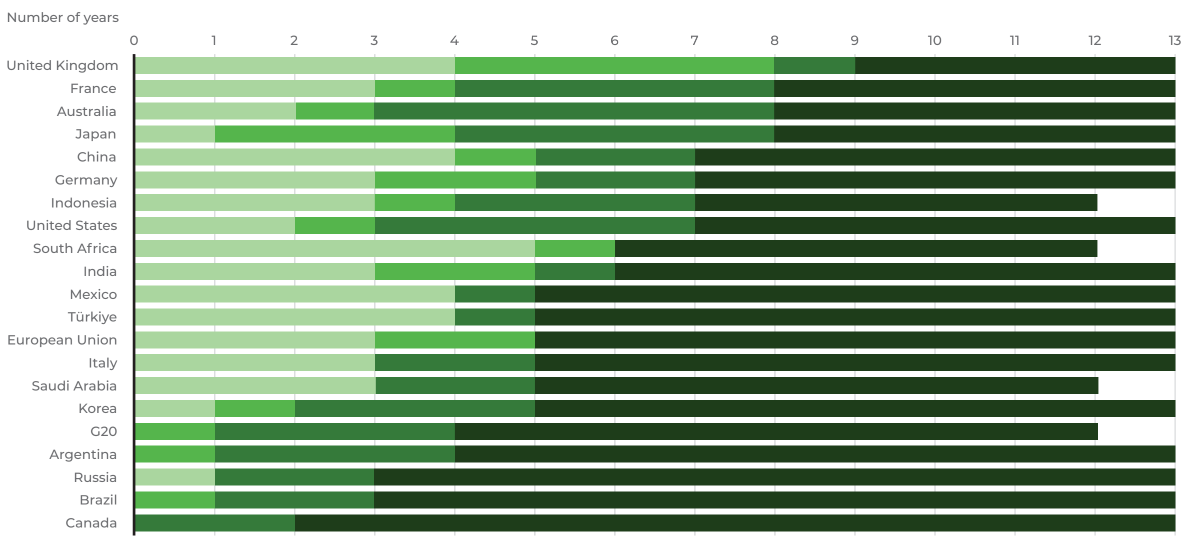


Figure 5: Energy Intensity Progress, Number of Years Above 2%, 3% and 4% for G20 Countries, 2010-2022. (Source: based on data from IEA (2023); https://www.iea.org/reports/energy-efficiency-2023/what-does-doubling-global-progress-on-energy-efficiency-entail#abstract)

effectiveness as a long-term strategy. First, energy efficiency gains are not incremental and unlimited – they approach an upper limit as technologies and processes near their maturity stage in their life cycle. As the "low-hanging fruit" of efficiency improvements is harvested, further advancements become increasingly costly and technically challenging, requiring more sophisticated technologies and substantial investments. This diminishing return poses a significant barrier to achieving continuous progress in energy efficiency, particularly in sectors where efficiency levels are already high. Further increase in energy efficiency at the economy level will come from the replacement of that product with another product, able to satisfy the same human need as effectively or more effectively than the disrupted product, but with lower energy intensity.

Secondly, energy efficiency often triggers a rebound effect, where reduced energy costs in the consumption basket can lead to increased energy use or related activities, offsetting some of the initial efficiency gains. This effect is particularly pronounced in regions with lower per capita energy consumption, such as Sub-Saharan Africa, where improved energy affordability can drive higher energy demand to meet unmet heating, cooling, or mobility needs).

Taken together, these recent trends underscore a critical insight: current progress is insufficient to meet global energy efficiency goal. While countries like those in the EU have demonstrated that policy and crisis response can drive substantial short-term gains, sustaining and scaling these improvements globally will require coordinated, long-term efforts. An enabling policy environment, mobilisation of more low cost finance as energy efficiency improvement requires higher upfront capital, and international cooperation will be indispensable for accelerating energy efficiency.

> The industrial sector remains the largest energy consumer worldwide, accounting for 39% of total final energy use.

In this regard, governments around the world are increasingly enhancing policy measures to unlock greater energy efficiency, especially in the wake of energy security concerns and climate commitments. Various energy efficiency policies are currently in effect worldwide, encompassing standards, financial incentives, market-based mechanisms, and regulatory measures. These policies are further complemented by the integration of pertinent technologies such as digitalisation and artificial intelligence. As a result of these concerted efforts, it is anticipated that the acceleration of energy efficiency improvements will gain momentum over the coming decades across all regions.

Sectoral Approach to Energy Efficiency – Buildings, Industry, and Transport

Global total final energy consumption reached around 445 exajoules (EJ) in 2023. The industrial sector accounted for the largest share at 39%, followed by the buildings sector (including appliances) at 28%, and transport at 27%, with the remaining 6% attributed to other end uses. Over the past decade, final energy consumption in advanced economies has declined by an average of 0.5% per year, while in emerging markets and developing economies (EMDEs), it has grown at an average annual rate of 2.6% (Figure 6). In 2023, EMDEs accounted for nearly two-thirds of global final energy demand and are expected to drive the future consumption growth due to rising living standards, increased prosperity, economic expansion and growing population.

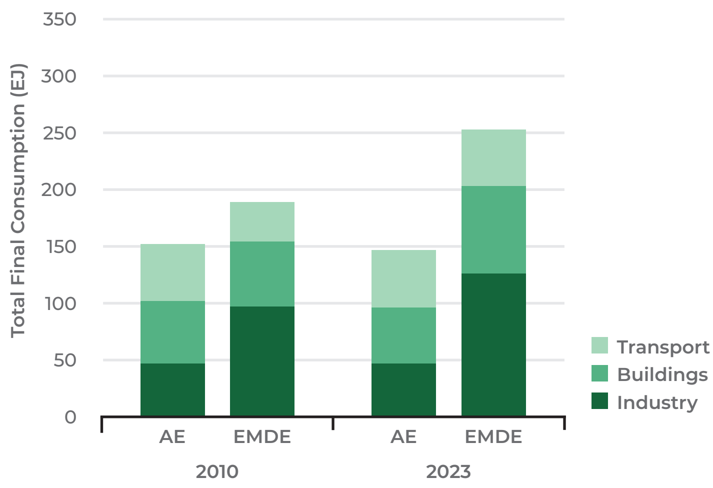


Figure 6: Total Final Consumption by Sector in Advanced Economies and Emerging Markets and Developing Economies, 2010-2023. (Source: IEA's World Energy Outlook 2024 extended dataset)

Greater efficiency progress across all end-use sectors can help mitigate rising energy demand. However, the pace of improvements and the nature of opportunities vary by sector, reflecting differences in technologies, consumption patterns, and implementation barriers. This section reviews the status of efficiency actions and trends in each sector, highlighting policies and measures that are driving improvements.

Buildings

Energy is used in buildings primarily for heating, cooling, lighting, water heating, and powering appliances and equipment. Improving building energy efficiency is widely seen as a "low-hanging fruit" of decarbonisation: buildings often contain many cost-effective efficiency opportunities, from insulating roofs and walls to upgrading air conditioners and lights, that can greatly reduce energy demand while improving comfort. As seen in Figure 7, significant progress has been made in some regions and countries, such as the EU and the United States, where energy consumption in buildings showed a declining trend between 2010 and 2023. Yet global building energy use continues to rise as floor area and appliance ownership increase, especially in developing economies. To change this trajectory, a combination of efficient building design, retrofits of existing stock, and high-efficiency appliances/HVAC (heating, ventilation, and air conditioning) systems is required.

One of the most fundamental building efficiency policies is implementing and enforcing building energy codes. Building codes set minimum energy performance

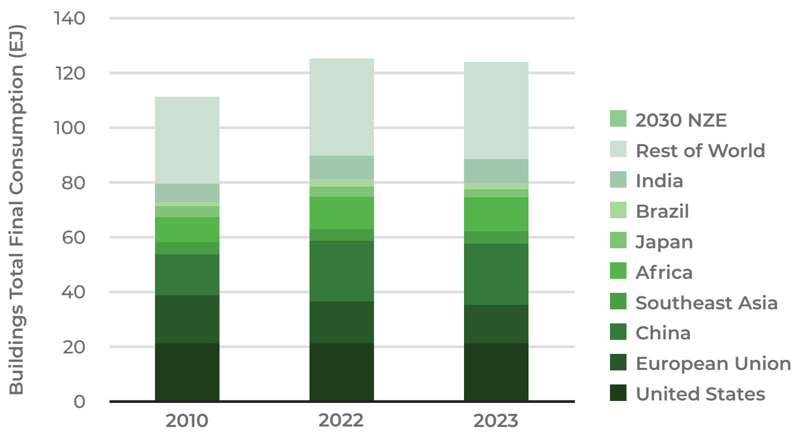


Figure 7: Total Final Energy Consumption for Buildings, 2010-2023. (Source: IEA's World Energy Outlook 2024 extended dataset)

requirements (for insulation, windows, HVAC efficiency, etc.) for new construction (and sometimes major renovations). Countries with long-standing codes (e.g. those in the EU, North America) have continually strengthened them, resulting in new buildings that are far more efficient than older ones. Many jurisdictions are updating their codes to move toward net-zero energy buildings.

For example, the EU's 2024 Energy Performance of Buildings Directive revision requires all 27 member states to not only enforce strict codes for new buildings (to be zero emission by 2030) but also to introduce MEPS for non-residential buildings, and mandatory long-term renovation strategies). This is a landmark step since the bulk of today's buildings will still be in use by 2050, especially in mature economies – meaning retrofitting is as important as efficient new builds.

In the United States, building codes are primarily governed at the state and local levels and many states update codes on a three-year cycle. Specifically, the 2022 update of California's Building Energy Code increased requirements for both insulation and efficient heat pumps). To address existing buildings, some jurisdictions are pioneering building performance standards. A notable example is New York City's Local Law 97, which caps permissible GHG emissions (a proxy for energy use) from large buildings and mandates owners of inefficient buildings to upgrade or face fines.

China has comprehensive building codes for urban buildings (covering insulation, windows, etc.) and is now enforcing them more strictly and extending them to rural housing. Japan and South Korea have some of the world's strictest building codes and are refining them. Japan is looking into performance-based standards that encourage advanced insulation and smart controls, while Korea's new Energy Intensity Target Management Programme targets energy use per floor area in medium and large buildings). Kenya made its building energy code mandatory in 2024, and included smart solutions in the code, starting from March 2025.

The number of countries implementing new or updating existing building energy codes has expanded in recent years. As of mid-2024, there were 85 mandatory building energy codes in place for residential buildings and 88 for non-residential buildings globally. However, despite this progress, more than 100 countries still lack mandatory requirements for energy efficiency in buildings. Some large countries with large populations like Nigeria are only beginning to adopt national building energy codes. In India, the new Energy Conservation Building Code for residences, known as Eco Niwas Samhita (ENS), is being developed and implemented with the goal of making it mandatory in various states.

Globally, nearly half of the new floor area isn't covered by mandatory efficiency codes yet. This poses a major challenge amid anticipated rapid construction growth in emerging markets and developing economies. Going forward, strengthening codes and expanding their scope (to cover renovations and smaller buildings) is considered a top priority to accelerate efficiency progress.

Building envelope improvements (insulation, air sealing, high-performance windows) are among the most impactful efficiency measures, as they reduce heating and cooling needs. In cold climates, insulating attics, walls, and upgrading windows can cut heating energy potentially by 30–50%. In hot climates, measures like cool roofs (reflective materials), urban forestry and insulation can similarly slash cooling loads. Such retrofits are being pursued in many countries via incentive programmes. Particularly, the EU has its Renovation Wave initiative, aiming to renovate 35 million buildings by 2030, and at least double the annual rate of energy renovations in the EU. The US funds weatherisation for low-income homes and offers tax credits for retrofits. China retrofitted over 400 million m² of residential floor space in northern heating regions during 2010s to improve insulation, and Japan provides subsidies for insulating older homes.

It is worth adding that high-performance building envelope measures (like super-insulation, triple-glazed windows) can cut heating/cooling needs by even 50–90%. One example of best practice is the Passive House standard which limits heating demand to about 15 kWh/m². Such buildings, though a small share, showcase the technical potential for ultra-efficiency.

Another crucial area is space heating and cooling systems. Space heating is often the single largest energy use in buildings in cold climates, while cooling is the fastest-growing use in warm regions. Heat pumps and high-efficiency air conditioners can dramatically lower energy consumption. Heat pumps have emerged as a game-changing technology. A heat pump can provide the same heat with 3-5 times less energy than an efficient gas boiler, by extracting ambient heat from the air or ground. Global heat pump deployment has recently accelerated, specifically in the EU. China and the US also have large heat pump markets. Today, over 100 million households globally use heat pumps as their main heater. The upfront cost of heat pumps has been a barrier, but many governments provide subsidies to boost their adoption.

For cooling, air conditioners (ACs) have become far more efficient over time – today's best available AC units can be 50% more efficient than average models, thanks to better compressors, fans, and refrigerants. Strengthening minimum energy performance standards (MEPS) and energy labelling for cooling appliances is a crucial factor. As of 2024, over 80% of global space cooling energy demand is subject to MEPS (since major markets like United States, EU, China, India, Middle East all have AC standards). In turn, international initiatives and regional efforts, such as the Cool Coalition or ASEAN SHINE (which harmonises AC standards), aim to raise cooling efficiency to mitigate an expected enormous growth in AC energy use. For example, Southeast Asian countries are promoting efficient cooling to counteract surging air-conditioning demand driven by rising temperatures and heatwaves.

The building sector also includes lighting and numerous appliances (refrigeration, electronics, etc.). Here, efficiency has seen significant progress. The global phase-out of incandescent and halogen bulbs in favour of LED lighting is largely complete in many regions, leading to 50-80% energy savings. LEDs went from less than 5% of global lighting sales in 2013 to over 50% in 2022, partially thanks to MEPS that phased out inefficient bulbs in over 100 countries. Some developing countries are still transitioning, but large-scale distribution of LEDs (often through utility programmes) is accelerating this shift.

For appliances like refrigerators, washing machines, and televisions, MEPS and labelling programmes (pioneered by countries like the United States, EU, Japan, Australia) have improved efficiency per appliance by 2-3% per year on average. For instance, a typical refrigerator today uses less than half the energy of one from the 1990s, despite often being larger and having features like frost-free operation. Meanwhile, appliance ownership is rising with increasing household income and expanding access to electricity. This improves living standards but also increases energy use. As an example of policy strengthening, Brazil implemented regulation on Energy Efficiency Indexes for refrigerators, targeting a 17% increase in efficiency from 2028.

Many countries are implementing mandatory labels in parallel to MEPS. While MEPS can aid in eliminating the worst-performing equipment from the market, labels help consumers notice the energy consumption of products, which can help them save money over the life of the appliance. For example, Japan's Top Runner programme (which uses average fleet targets by manufacturer) and the EU's rescaled A-G appliance labels both aim to pull the market toward higher efficiency classes. Developing economies in Association of Southeast Asian Nations (ASEAN) and Latin America have fairly comprehensive labelling (e.g., Thailand's 5-star system and Brazil's Procel seal). An interesting case is India's Standards & Labelling (star rating), which has led to significant improvements: Indian ceiling fans and ACs, for instance, have become 30-50% more efficient on average since labels were introduced, initiated with a voluntary system and later made mandatory.

A special subset of building energy is cooking. In developing countries, clean cooking initiatives (e.g. switching from traditional biomass stoves to modern efficient cookstoves or electric induction cooktops) are both public health and energy efficiency priority. Traditional open-fire stoves can waste 80-90% of the fuel's energy and cause indoor air pollution. Efficient cookstoves or electric cooking can dramatically cut fuel use.

Importantly, over two billion people globally continue to rely on polluting fuels for cooking, posing severe health risks and environmental challenges. These energy

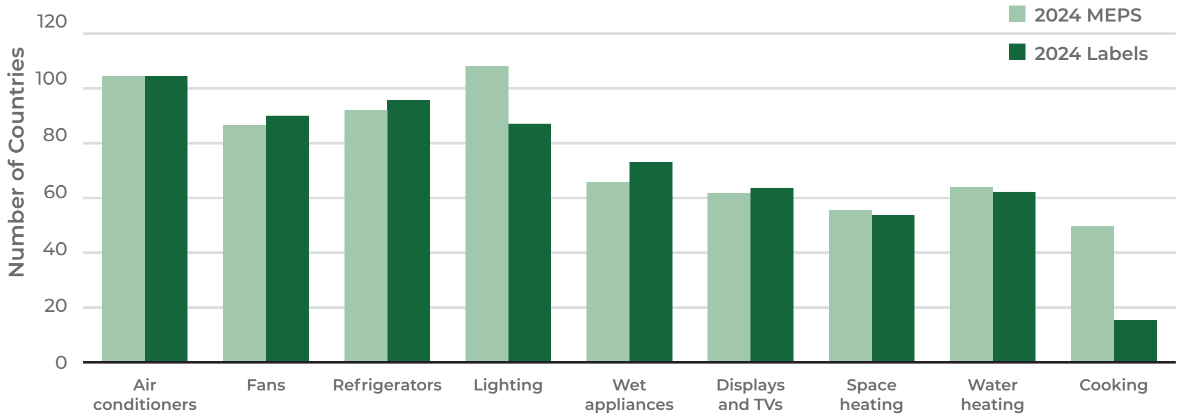


Figure 8: Number of Countries With Minimum Energy Performance Standards and Labels for Appliances, Global, 2024. (Source: IEA's Energy Efficiency report 2024)

access disparities are particularly critical in regions experiencing rapid population growth, such as Sub-Saharan Africa. Accelerating the transition to clean cooking solutions in these regions not only enhances universal access to affordable, reliable, and sustainable modern energy but also contributes meaningfully to improving energy efficiency, since much less wood or charcoal is burned for the same cooking service.

From a systems perspective, smart buildings and digitalisation are helping optimise energy use. Building energy management systems (BEMS) in commercial buildings can cut energy 10-20% by automatically controlling HVAC, lighting, and other systems based on occupancy and need. In homes, smart thermostats and connected devices allow for dynamic control and participation in demand response programmes (shifting usage to off-peak times), which improves overall system efficiency.

Industry

Industry is the largest final energy-consuming sector, accounting for nearly 40% of global final energy demand, equivalent to 170 EJ in 2023. Between 2010 and 2023, global industrial energy use increased at an average rate of around 1.5% per year (Figure 9). However, this global trend conceals important regional divergences. In advanced economies, industrial energy demand has either stabilised or declined. For instance, industrial energy use in the EU declined by 1% annually over the period, while Japan experienced a more pronounced reduction of 1.8% per year.

By contrast, developing economies recorded substantial increases, reflecting both rapid economic growth and industrial expansion. India's industrial energy demand grew at an average annual rate exceeding 5% over period, while China saw growth of around

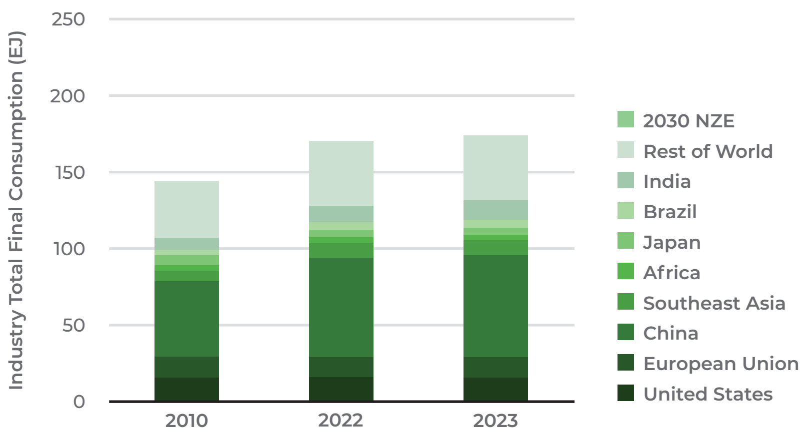


Figure 9: Total Final Energy Consumption for Industry, 2010-2023. (Source: IEA's World Energy Outlook 2024 extended dataset)

2% per year. Currently, China alone accounts for 38% of global industrial energy consumption. Although importantly, China's GDP grew much faster, its industrial energy intensity improved significantly.

Industrial energy use is dominated by energy-intensive industries – notably iron and steel, cement, chemicals and petrochemicals, aluminium, glass, pulp and paper, and refining – as well as a broad range of lighter manufacturing. A significant portion of industrial energy is used to produce high-temperature heat and to drive machines (motors). Improving industrial energy efficiency is crucial for reducing fuel consumption and emissions, as well as for improving industrial competitiveness through lower operating costs. Simultaneously, as industrial output is set to grow, particularly in developing economies, industrial energy use can rise even if processes become more efficient, making continuous improvements necessary just to stabilise consumption.

Industrial energy efficiency can be improved through both process optimisation and technology upgrades. A core strategy is adopting the best available technologies for each process. For example, in steel production, modern electric arc furnaces are far more energy-efficient (and use recycled scrap as input) than traditional blast furnace-basic oxygen furnace routes for appropriate applications, especially when recycling scrap steel.

The Steel Manufacturer's Association claims that electric arc furnaces produce twice the steel with 75% less GHG emissions over basic production. In cement manufacturing, upgrading to efficient kilns (dry-process kilns with preheaters and precalciners) and using waste heat recovery to generate power can significantly cut net energy use. This is a major opportunity across industries: capturing exhaust heat from furnaces, kilns, or engines and using it to produce steam, power, or preheat materials. Some countries have policies to encourage the most efficient processes available. China, for instance, through its Top 1000/Top10000 Enterprises programmes and now through sector-specific action plans, has pushed major industrial firms to upgrade to advanced technologies and recover waste heat.

Another opportunity is upgrading and optimising electric motor systems. Motors are ubiquitous in factories (running pumps, fans, compressors, conveyor belts, machine tools, etc.), and account for about 70% of industrial electricity use globally. Efficiency improvements in motor systems, such as adopting high-efficiency motors, adding variable speed drives to adjust motor output to actual needs, can yield huge energy savings. Schneider Electric highlights that installing modern motors can drastically reduce energy consumption, in some cases by up to 50%.

Importantly, many countries are stepping up their efforts to reduce industrial energy consumption through the implementation of MEPS for electric motors, referred to as an international efficiency (IE) class. In 2010, only 13 countries had MEPS in place for motors, covering about 17% of global motor energy consumption. Since then, substantial progress has been made. By 2023, more than 60 countries had adopted MEPS for electric motors, expanding coverage to nearly 57% of global motor energy use. Strengthening and broadening these standards is increasingly recognised as a critical strategy.

Several countries are advancing policy initiatives. China, for example, has issued draft revisions for two mandatory national standards, specifically targeting the energy efficiency grades and MEPS for motors. These revisions are accompanied by implementation guidelines for motor replacement, upgrade, and recycle. Egypt identified efficient motor regulations as among key mitigation actions within its second NDCs update and aims to allocate USD 11.6 billion to efficient motors under industry projects.

In addition to greater coverage, the stringency of MEPS for motors is crucial and improving. Many countries still allow the sale of motors with subpar efficiency (IE1 or IE2 levels) whereas the most efficient and commercially available currently are classified as IE5. The EU, the United Kingdom (UK) and Turkey lead the way by requiring the IE4 standard in new motor sales. South Korea is also targeting IE4, with the aim of implementing the new standard by 2026. Brazil, China, the US, and Canada have broadly adopted IE3 as mandatory.

Industrial energy management is another pillar of efficiency. Many large companies are implementing Energy Management

Systems (EnMS) and pursuing ISO 50001 certification, which involves a systematic approach to monitoring and reducing energy use. Such practices often uncover "low-cost" measures (better maintenance, reducing leaks in compressed air systems, insulating steam pipes, etc.) that can trim energy use by a few percent with minimal investment. Over time, continuous improvement through EnMS can yield significant cumulative savings. More generally, there are signs of increased policy focus on EnMS and governments encourage this including via mandates. For example, the EU adopted a recast of the Energy Efficiency Directive requiring enterprises with an energy use above 85 TJ to implement EnMS). Canada provides funding for the implementation of efficiency solutions in industry, including EnMS, through the Green Industrial Facilities and Manufacturing Program.

An important trend in industry is electrification, particularly in applications where it is technically and economically feasible. Electrification not only enables the use of cleaner energy sources, especially as power grids decarbonise, but also improves point-of-use efficiency and reduce onsite energy losses. While certain high-temperature processes in heavy industries remain difficult to electrify, many low- and medium-temperature processes are suitable for electric alternatives. Technologies such as industrial heat pumps, electric boilers, infrared heaters, and induction furnaces offer efficient replacements for fossil fuel boilers. For example, in China the electrification of process heating in light industry has seen strong positive progress. From 2010 to 2022, electricity as a heating source in light industry grew from 18% to 35%, as industrial players phased out the use of coal-based methods. China's new Carbon Peaking Implementation Programme for Key Areas of Light Industry aims to further phase out coal energy use, placing a stronger emphasis on electrification. EU countries, such as France and Germany, have programmes to help industries replace old gas boilers with electric heat pumps for process heat.

Several cross-cutting technologies are gaining momentum. A key area is material efficiency – using less material for the same product (e.g. thinner steel for cans, alternative cement blends) indirectly saves the energy that would have been used to produce those materials. While not a traditional energy efficiency technology, circular economy approaches like recycling and reusing materials can dramatically reduce industrial energy demand. For example, producing recycled aluminium uses significantly less energy than primary production, with an estimated 95% less energy required. Many countries' strategies, especially for hard-to-abate sectors, include circular economy measures (e.g. the EU's Circular Economy Action Plan).

The shift to more digital, automated industry also aids efficiency. Industrial digitalisation, for instance, using AI and IoT for predictive maintenance and process optimisation, can improve efficiency by minimising downtime and keeping processes at optimal settings. Companies are increasingly using sensors and AI to detect inefficiencies like steam leaks or suboptimal combustion in real time.

Mobility

From 2010 to 2023, total final energy consumption in the transport sector increased on average by 1.45% per year. Around 44% of transport energy consumption is from the three largest energy consumers, the US, the EU and China (Figure 10). While electrification is gathering pace, oil products still dominate the sector, providing over 90% of its final energy use.

Improving energy efficiency in the transport sector presents unique challenges, given its reliance on millions of individual vehicles, a diversity of transport modes, and behavioural factors and infrastructure-related constraints. Nevertheless, steady progress is being driven by both technological innovation and supportive policy frameworks. While the rapid penetration of electric vehicles (EVs) offers a transformational leap in efficiency, conventional vehicles also continue to benefit from incremental improvements through stronger fuel economy standards and innovations in engine technology. In parallel, segments such as aviation and shipping are actively pursuing energy efficiency gains through technological enhancements and fuel-saving operational practices. Road transport, which accounts for about 75% of total transport energy demand, remains the central focus of energy efficiency, driven also by decarbonisation efforts.

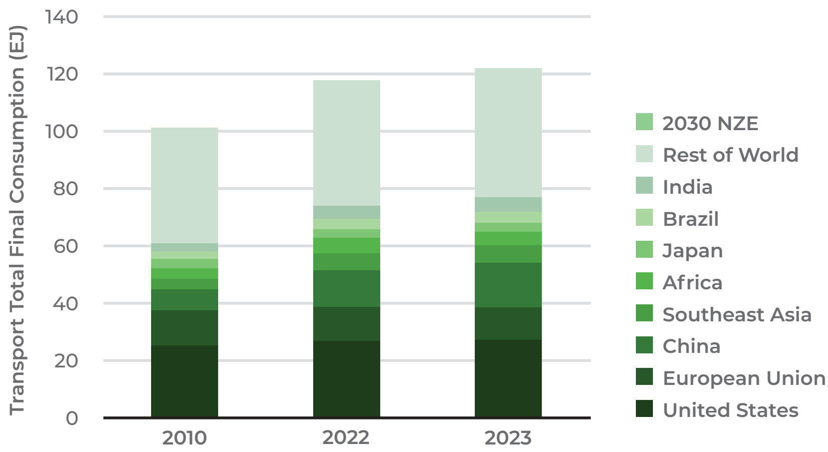


Figure 10: Total Final Energy Consumption for Transport, 2010-2023. (Source: IEA's World Energy Outlook 2024 extended dataset)

For light-duty vehicles, fuel economy standards have been the main policy lever to improve efficiency. Since the early 2000s, the EU, Japan, China, the US, and many other countries have implemented progressively tightening standards. However, the rate of improvement globally has been modest in the last decade – on the order of 1–2% per year, which is only about half of what was targeted under Global Fuel Economy Initiative, calling for 3–4% per year improvement. The slowdown was partly due to consumer preferences shifting to larger vehicles (SUVs) which offset efficiency gains.

Recent years saw notable regulatory moves. In March 2023, the EU strengthened the 2030 tailpipe emissions reduction target for new cars from 37.5% to 55% by 2030 compared to 1990 levels and introduced a 100% reduction for 2035. In April 2024, the US updated its Corporate Average Fuel Economy (CAFE) standards for passenger cars, with a 2% annual increase in fuel efficiency required from model years 2027-2031. China has progressively strengthened its fuel consumption limits for passenger cars and in 2024 launched subsidies to accelerate scrapping of used fossil fuel-powered vehicles with new energy or fuel-efficient vehicles. Australia passed its first fuel efficiency standards in 2024 to reduce new car emissions by 60% by 2029. Other countries are following suit.

Overall, these standards and policies mean each new generation of vehicles uses less fuel than the last, contributing to aggregate efficiency gains as the fleet turns over. Simultaneously, modern internal combustion engines vehicles employ a suite of efficient technologies: hybrids, turbocharging, downsizing engines, light-weighting, direct fuel injection, better aerodynamics, low rolling resistance tires, etc.

Electrification of global vehicle fleet will further contribute to efficiency gains. Drive trains are inherently far more efficient at converting energy into motion (see box 4.1). In 2023, about 18% of global new car sales were electric, double the share of just two years earlier. In 2024, electric car sales exceeded 17 million globally, reaching a sales share of more than 20%. Global EV growth is underpinned by charging infrastructure development and adoption of increasingly ambitious strategies for promoting zero-emission vehicles in a range of countries. The implementation of forward-looking sales restrictions on new diesel or petrol vehicles will further support electric mobility. For example, the EU's mandate for 100% zero-emission car sales by 2035 ensures that by then all new cars will be highly efficient EVs. Canada announced its New Electric Vehicle Availability Standard in December 2023, which includes a target that 100% of new vehicle sales will be EVs by 2035. China aims to make pure EVs the mainstream of new car sales by 2035.

Moreover, electric drivetrains are being adopted in other segments, with electric buses becoming increasingly common in urban areas – led by China's deployment of millions of e-buses – and electric two- and three-wheelers replacing petrol motorbikes in many Asian and African countries, delivering significant air quality and pollution reduction benefits alongside energy savings. India is a vivid example, with electric two-wheeler sales increasing fivefold and three-wheeler sales tripling over the past three years, largely supported by the FAME (Faster Adoption and Manufacturing of Hybrid and Electric Vehicles) scheme. This segment constitutes over 80% of the country's total EV sales.

Heavy-duty vehicles (HDVs) are critical for improving transport efficiency due to their high fuel consumption. Historically, efficiency standards for HDVs have been limited or absent in many countries, but this is now changing as fuel economy regulations begin to target this segment. The EU in 2024 expanded its CO_2 standards to cover 90% of new trucks, with a target of 45% emissions reduction by 2030. The US adopted Phase 3 truck standards to start in 2027, which are 40–60% stricter than current ones (. China's new fuel consumption standard for HDVs, Stage 4, will take effect on July 2025, and tighten consumption limits by 12%–16%, compared to the previous one. These are just several examples, but overall trend will bring more efficient engines, more hybridisation and accelerate the adoption of electric trucks into the freight sector.

Efficiency in transport isn't only about vehicles – it's also about using them smarter. Logistics improvements, such as better routing of trucks, reducing empty backhauls, and optimising supply chains, can cut fuel use in freight. Digital platforms and AI are increasingly used in trucking to minimise unnecessary mileage and idling. Urban planning and public transport improvements encourage shifts from private car use to more efficient modes (buses, metro, biking, walking), saving energy on a per passenger-km basis. These are broader policy areas (beyond the scope of pure energy efficiency policy), but they are part of an integrated approach to efficient transport systems.

Conclusion

Energy efficiency has firmly emerged as a foundational pillar in global climate and energy strategies, offering one of the most immediate, cost-effective, and scalable means of reducing GHG while enhancing energy security and economic productivity. Once perceived as a secondary concern, efficiency is now increasingly recognised as a strategic energy resource – the “first fuel” – with the potential to deliver transformative outcomes across economies. From its conceptual origins during the oil crises of the 1970s to its central role in the COP28 commitment to double global energy efficiency progress by 2030, the trajectory of energy efficiency highlights its growing significance in addressing the global energy trilemma.

Global and regional trends reveal both encouraging opportunities and persistent challenges. While the 2010–2019 period was marked by steady improvements in energy intensity, recent years have witnessed a slowdown due to post-pandemic recoveries and energy-intensive growth in developing economies. Nonetheless, the energy crisis of 2022 catalysed a renewed focus on efficiency, prompting policy tightening, public awareness initiatives, and accelerated investment in advanced technologies. The record high USD 660 billion invested in energy efficiency in 2024 signals positive momentum, but further scaling and institutional support will be essential to meet the ambitious targets outlined at COP28.

Sectoral analysis confirms that significant untapped potential remains across buildings, industry, and transport. Advances in building envelopes, heat pumps, and efficient appliances are reshaping energy use in the residential and commercial sectors. In industry, process optimisation, digitalisation, and electrification offer pathways to boost competitiveness while reducing emissions. Meanwhile, the transport sector is experiencing a profound shift through improved fuel economy standards and the rapid adoption of EVs. Electrification emerges as a cross-cutting enabler, delivering direct efficiency improvements across all major end-use sectors.

However, the path forward is not without limitations. As technologies mature, incremental efficiency gains become more difficult and expensive to achieve. In parallel, rebound effects, especially in regions with significant unmet demand, may offset part of the progress. Addressing these challenges requires a comprehensive approach that couples efficiency improvements with robust policy frameworks, targeted investments, and supportive behavioural and demand-side strategies. Ultimately, more than a tool for reducing consumption, energy efficiency should be seen as a catalyst for system transformation, paving the way for a more sustainable, resilient, and inclusive energy future.



12

CHAPTER 12

THE SEARCH FOR CRITICAL MINERALS: CHALLENGES AND OPPORTUNITIES

The global shift toward renewable energy technologies and electric mobility has dramatically intensified the demand for certain critical minerals. Among these, lithium, cobalt, nickel, and rare earth elements (REEs) have emerged as essential to the energy transition. These minerals are indispensable for the production of batteries, wind turbines, electric motors, and other clean technologies. These minerals are not only essential for the clean energy transition, but they also pose significant supply chain and geopolitical risks. As global competition intensifies over access to these minerals, the fragility and strategic importance of their supply chains have come into sharp focus.

As nations recognise the strategic importance of critical minerals for clean energy, technology, and economic security, several countries have emerged as leaders in developing integrated and forward-thinking critical mineral strategies. Best practice recommends that such strategies address the problems and concerns associated with traditional mining practices. Tailings and acid mine drainage are major hazards, and mining in sensitive areas (e.g., tropical forests or deep sea) amplifies ecological risks. Concerns relating to deforestation, habitat destruction, soil erosion, water pollution, and greenhouse gas emissions are receiving more focus and attention from interested and affected parties. Sustainable mining seeks to reduce these impacts through better technologies, environmental safeguards, and community engagement.

This chapter explores the drivers of rising demand for critical minerals, the technological and geopolitical implications, and the environmental and social considerations associated with the extraction and use of these key minerals. The key vulnerabilities in critical mineral supply chains and the geopolitical dynamics shaping global access and control over these essential resources are also explored. The chapter further examines some selected case studies of countries that are actively pursuing sustainable, secure, and innovative approaches to critical mineral management, highlighting key policies, industrial initiatives, and international cooperation efforts driving their success. ▸

The Increasing Demand for Key Critical Minerals

Demand for Lithium

Lithium can be seen to be the foundation of battery power as it is considered central to lithium-ion batteries used in electric vehicles (EVs), electronics, and energy storage. Major producers include Australia, Chile, and China. The demand for lithium is rising at an unprecedented pace. Between 2023 and 2030, global lithium demand is projected to increase 3.5 times. This expected surge reflects the transition to electrification across multiple sectors as businesses and governments embrace greener energy solutions.

As the world accelerates its shift toward green energy, lithium has become a critical mineral driving that transformation, leading to skyrocketing demand for lithium-ion batteries in EVs and energy storage systems. The recent surge in demand for lithium poses an interesting challenge – ensuring that supply can keep up with the demand and balancing demand and supply to maintain an appropriate price for lithium.

Most analysts see a looming large potential supply gap and believe that, despite production increases, the industry is nearing a serious supply shortfall. By 2029, global demand could exceed supply, requiring more lithium in a single year than was mined worldwide between 2015 and 2022. Projections indicate that by 2034, global demand for lithium could be 6.5 times greater than in 2023, further widening the supply-demand imbalance. By 2029, the industry may reach a tipping point where demand outstrips supply, creating significant challenges for the global energy transition.

However, due to production cuts, shifting demand patterns, geopolitical tensions, and the uncertainty of United States-China trade tensions, the lithium market in 2025 is expected to face significant challenges. Consequently, a bullish outlook for lithium should be cautiously based on the realisation that the market is likely to face challenges in the coming years. There is a growing sense among market participants and industry analysts that the market balance could be much tighter in 2025.

Demand for Cobalt

Cobalt enhances battery performance and remains key to high-performance EV batteries, although alternatives are beginning to emerge. In the petrochemical industry, cobalt-oxide is used as a catalyst in the process of refining crude oil. The green energy transition, particularly the resultant need for battery storage capacity, has created a rapidly increased global demand for cobalt.

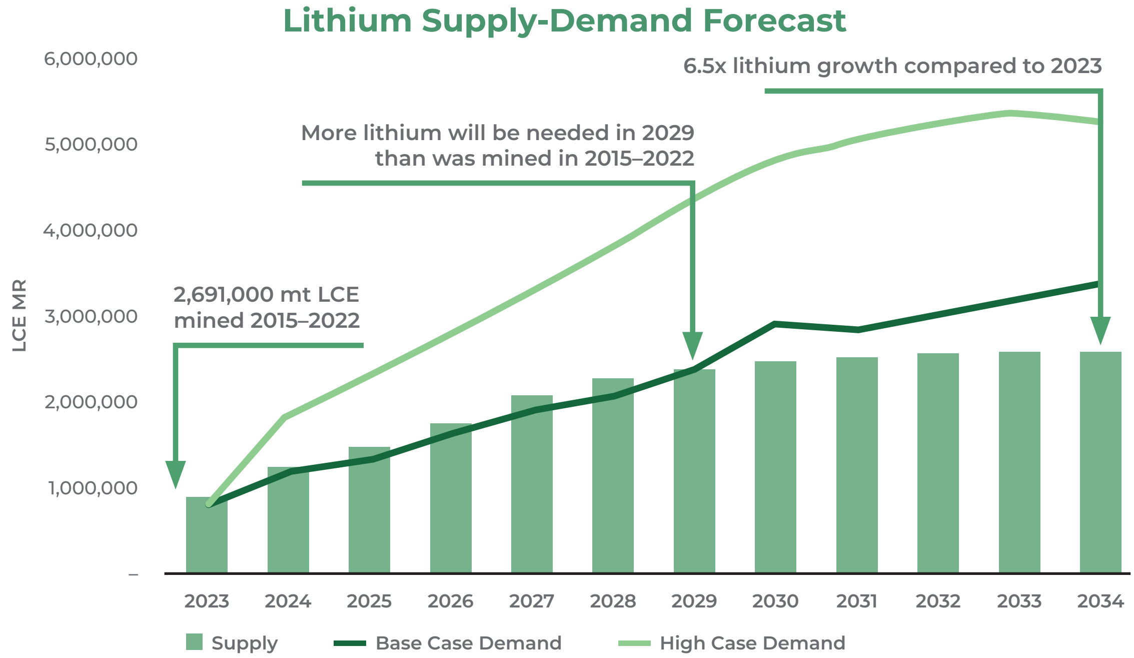


Figure 1: Forecast for Increasing Demand for Lithium. (Source: Lithium Harvest Blog, 2025)

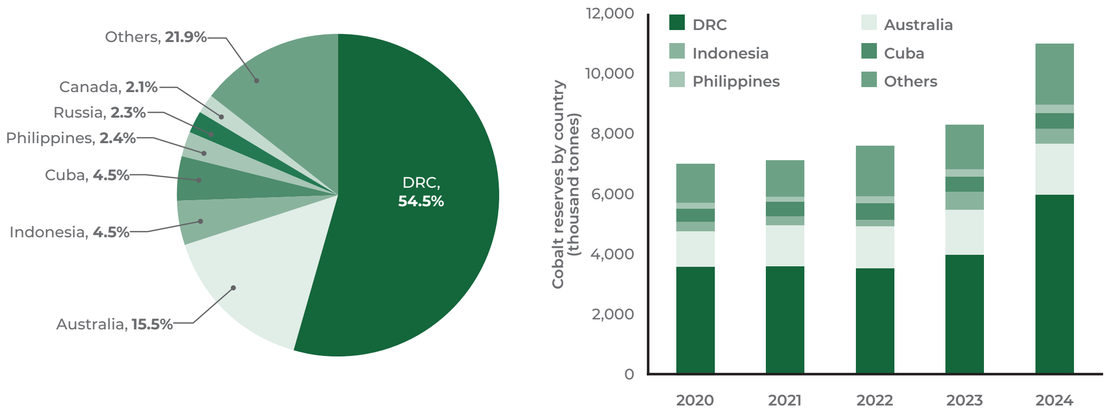


Figure 2: Global Cobalt Reserves. (Source: MINE In Depth Report, 2025)

The widespread demand uptick for battery raw materials resulted in the ballooning of cobalt supply over the last five years, with annual mine supply of the critical metal growing from 140,000 metric tons in 2020 to 290,000 metric tons in 2024. This 107 percent increase has far outpaced rising demand from the EV sector and other end-use segments, leading to a massive oversupply. However, within the global hierarchy of critical minerals that miners are racing to extract, cobalt remains highly sought after.

In addition to its uses in EVs, this transition metal that is generally mined as a by-product of copper or nickel, is also used for a range of essential applications across defence, aerospace, energy storage, and consumer electronics.

With production rising internationally, cobalt pricing has been volatile. Following its peak in 2018 at $81,900 per tonne (t), the metal is at a multi-year low due to oversupply and a shift towards lithium-iron-phosphate (LFP) batteries that are considered more cost-effective and thermally stable. However, it appears that the cobalt market is enduring a sustained period of market weakness, which is expected to persist as supply outpaced demand, extending market surpluses, with prices expected to remain under pressure in the short term.

Most analysts hold the view that strong demand growth is expected to outstrip supply from the mid to late 2020s, when prices are forecast to recover to incentivise further supply investment and support rising future market demand.

Demand for Nickel

Nickel is used in high-energy cathodes and stainless steel. Nickel demand is surging and set to triple by 2030. This surging demand is driven by its critical role in EV batteries, stainless steel, and defense applications.

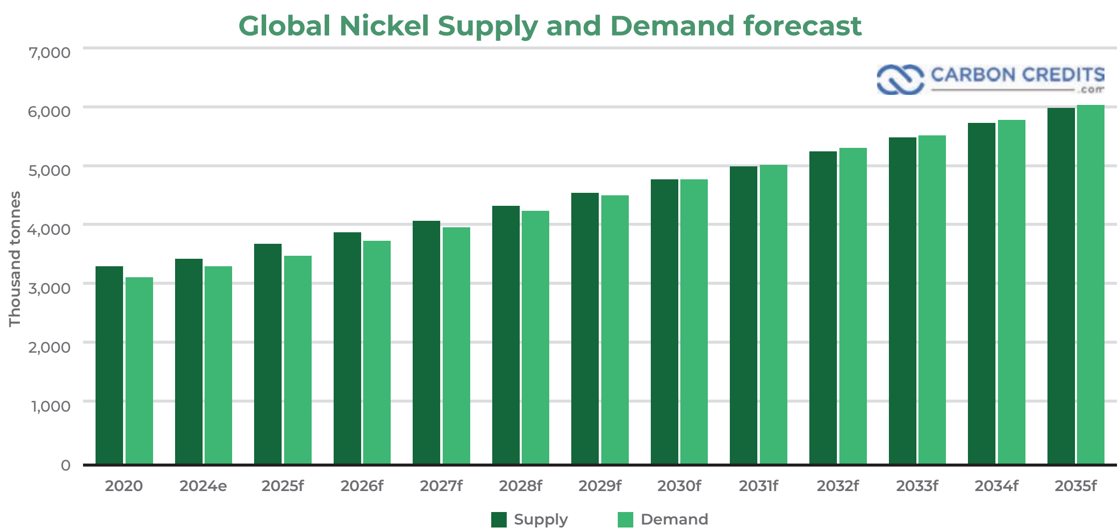


Figure 3: Global Nickel Supply and Demand Forecast. (Source: Carbon Credits, 2025)

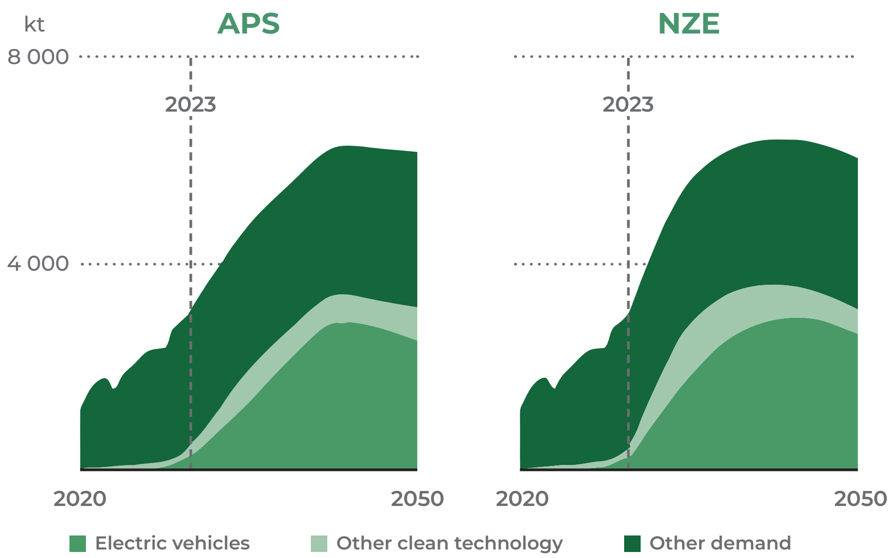


Figure 4: Demand Outlook for Nickel (2010-2015) – Announced Pledges Scenario (APS) and the Net Zero Emissions by 2050 (NZE). (Source: IEA Report, 2024)

Most analysis of supply versus demand paints a picture of demand growing at a faster rate than supply. Over the period from 2023 to 2035, the compound annual growth rate (CAGR) for supply is 4.6%, while demand is projected to grow at 5.1%. Based on this supply and demand forecast, the current nickel oversupply and low-price environment are expected to shift.

While the nickel market is currently facing persistent challenges of oversupply, slower demand growth, and stricter environmental regulations, by 2030 and beyond, demand is projected to exceed supply, leading to a further price increase. Over the past five years, the cumulative value of imported nickel grew by an average of 4.8%, increasing from $4.96 billion in 2019, reaching a global nickel imports value of $5.2 billion in 2023.

Demand for Rare Earth Elements

Rare earth elements play a vital role in clean technologies. Achieving the ambitious targets of the 2016 Paris Agreement—which calls on signatory nations to cut emissions and limit global temperature rise—will require massive deployment of wind turbines, solar panels, EVs, and energy storage

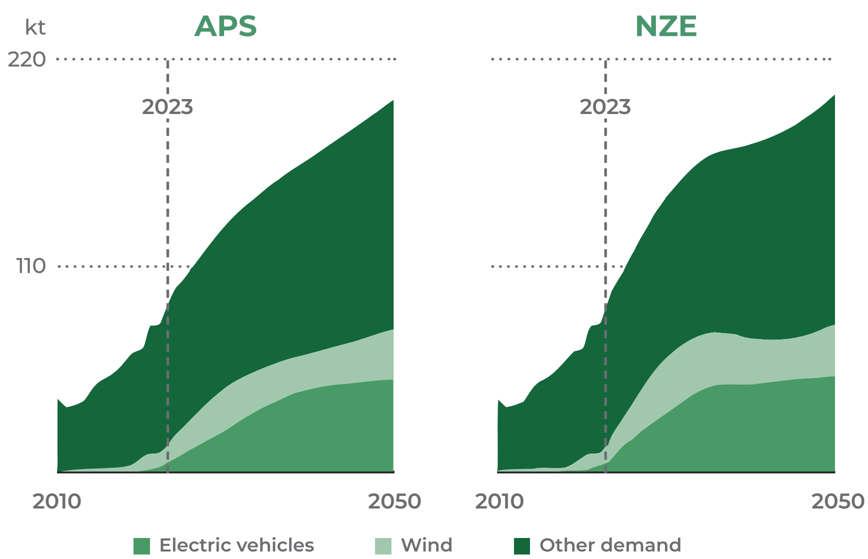


Figure 5: Demand Outlook for Rare Earth Elements (2010-2015) – Announced Pledges Scenario (APS) and the Net Zero Emissions by 2050 (NZE). (Source: IEA Report, 2024)

systems. These technologies depend heavily on rare earth elements and other critical minerals. Beyond clean energy, rare earths are also essential in a wide array of applications, including consumer electronics, EV motors, aircraft engines, medical devices, oil refining, and military systems such as missiles and radar.

The rare earth elements are a group of 17 elements including 15 silvery-white metals called lanthanides, or lanthanoids, plus scandium and yttrium. They are not rare in the sense that they are uncommon; some are more common than lead, for example, but they are seldom found in sufficient amounts to be extracted easily or economically. They tend to be spread thin around the Earth's crust in small quantities and mixed together or with other minerals, so larger deposits are difficult to find and costly to extract.

According to the International Energy Agency, demand for rare earth elements is expected to reach three to seven times current levels by 2040. The IEA report indicates, while the global supply of critical minerals needs to quadruple within the Paris Agreement time frame, the current rate of supply is only on track to merely double. The demand for rare earth elements is expected to grow 400-600 percent over the next few decades.

Most wind turbines use neodymium–iron–boron magnets, which contain the rare earth elements neodymium and praseodymium to strengthen them, and dysprosium and terbium to make them resistant to demagnetisation. Global demand for neodymium is expected to grow 48 percent by 2050, exceeding the projected supply by 250 percent by 2030. The need for praseodymium could exceed supply by 175 percent. Terbium demand is also expected to exceed supply. To meet the anticipated demand by 2035 for rare earth elements, one analysis projected that over 300 new mines would be needed.

Supply Chain Risks and Geopolitical Challenges in Critical Mineral Sourcing

Concentration of Production and Refining

Today, approximately 90% of the world's lithium production is concentrated in just four countries: Argentina, Australia, Chile and China. Australia is currently the largest lithium producer, contributing over 40% of global lithium output in 2023, primarily through the extraction of spodumene ore. Australia's production relies heavily on hard rock mining, which involves extracting spodumene ore, while countries like Chile and Argentina utilise their vast continental brine reserves to extract lithium. This geographical distinction highlights the diversity in extraction methods across regions. In South America, brine operations dominate, while ore mining is the leading method in Australia.

Despite Australia's mining dominance, China processes most of Australia's lithium ore, refining it into battery-grade products and ultimately controlling a significant portion of the global lithium supply chain.

The Democratic Republic of the Congo (DRC)is the dominant player in global cobalt production, estimated to account for just over 80% of global output, followed by Indonesia at 6.7%. While still far behind the DRC, production from Indonesia's cobalt mines has surged over the past decade, jumping from 1.3kt in 2015 to 20.4kt in 2024. The country has surpassed its competitor Russia to become the second-largest cobalt producer globally. Despite Russia's substantial cobalt reserves, the ongoing conflict in Ukraine has triggered severe sanctions and trade restrictions led by the EU and United States, hindering Russia's ability to reliably supply to the global market. Consequently, national cobalt production is projected to stagnate at 3.1% of the total global production, until the end of the decade.

Australia and Canada are also becoming key players as market diversification expands. In 2024 they accounted for only 1.9% of the global share but this is projected to increase to 6% by 2030 due to new projects such as Australia's Broken Hill Cobalt and Canada's Copper Cliff mine.

Intertwined throughout the global cobalt supply chain is China, with national state-supported mining companies owning

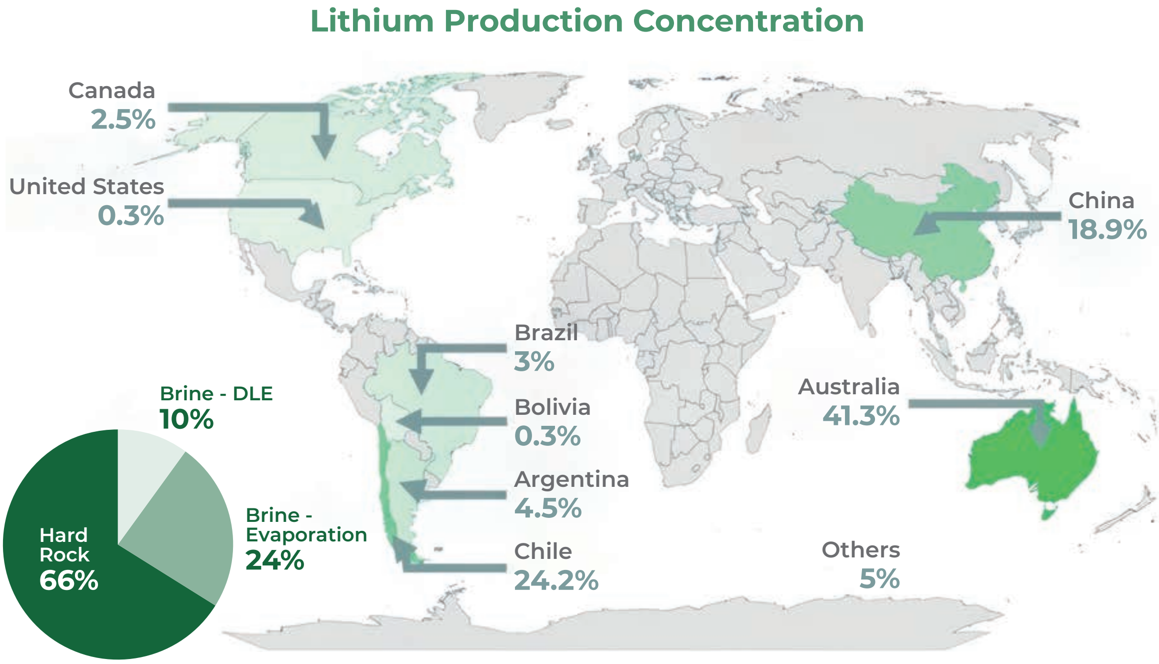


Figure 6: Global Lithium Production Share by Country. (Source: Lithium Harvest Blog, 2025)

and operating significant assets in key cobalt mining jurisdictions, establishing what some market watchers are calling "a near monopoly". Since 2008, for example, China and the DRC have operated under an 'infrastructure for minerals deal'. The deal was revised at the beginning of 2024 to include a commitment of up to $7bn in infrastructure projects in the DRC in exchange for continued access to its abundant mineral resources. In Indonesia, Chinese-backed investments have developed advanced high-pressure acid leach (HPAL) facilities to boost local nameplate capacity of cobalt. China operates, in Indonesia, the largest HPAL facility in the world and Chinese companies have built 90% of domestic nickel smelters in Indonesia.

The supply of nickel is dominated by Indonesia and the Philippines, with the global supply chain being increasingly concentrated in Indonesia and controlled by Chinese interests, raising serious concerns for the West. With the United States and its allies scrambling to secure alternative sources, Canada is emerging as a strategic supplier of choice. This situation could be further exacerbated by the recent Trump administration's widespread tariffs on United States trade partners.

China dominates refining, prompting geopolitical concerns. The country accounts for about 60% of global mine production and 90% of processed and permanent magnet output. Beijing sets quotas on output,

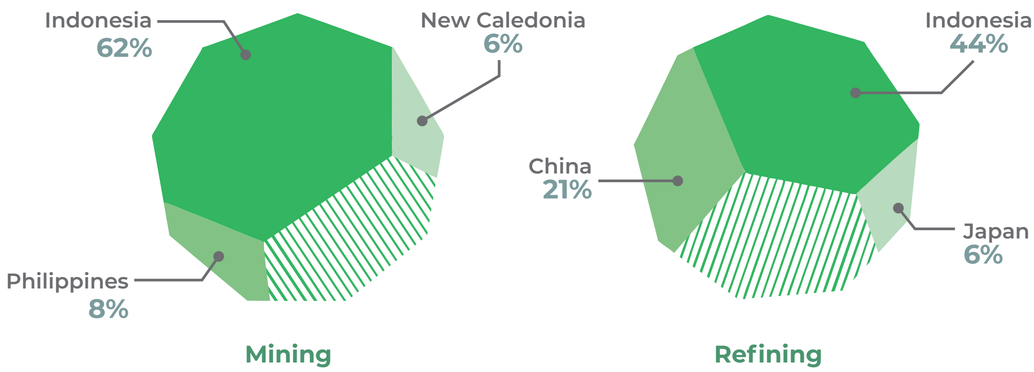


Figure 7: Top Three Nickel Producers Projected for 2030. (Source: IEA Report, 2024)

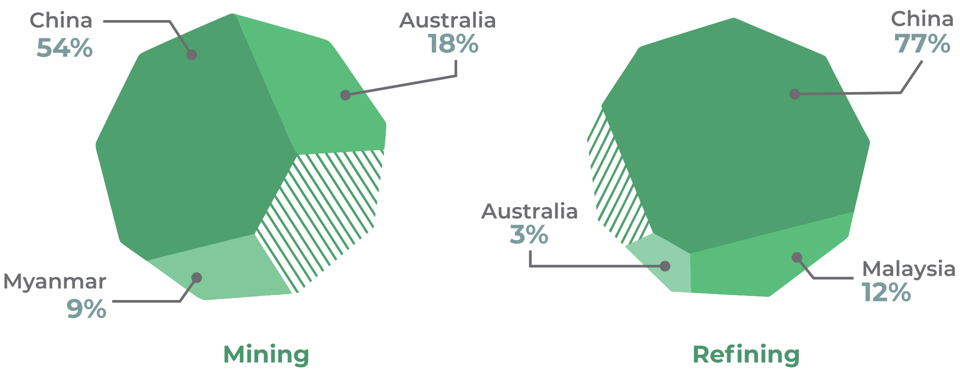


Figure 8: Top Three Producers for Rare Earth Elements, Projected for 2030 (Source: IEA Report, 2024)

smelting, and separation, which are closely monitored as a barometer of global supply.

The global supply of many critical minerals is highly concentrated in a small number of countries, with over 70% of cobalt coming from the DRC, China refining more than 80% of rare earth elements (REEs), Indonesia and the Philippines dominating nickel production, and Australia, Chile, and China leading lithium extraction.

China continues to dominate the market for rare earth elements, although companies in the United States and other countries are seriously scrambling to catch up.

Vulnerabilities in the Supply Chain

Critical mineral supply chains are long, complex, and poorly diversified. The current geographic concentration of critical minerals increases the risk of supply disruptions due to political instability, trade restrictions, or environmental policies in key producing nations. The supply chain of critical minerals is vulnerable to the following risks: export bans, resource nationalism, geopolitical rivalries, transportation bottlenecks, pandemics, natural disasters, price spikes and demand-supply mismatches.

China's grip on cobalt has intensified anxieties around dependency in the United States, where the focus on critical minerals security and 'foreign entities of concern' is set to escalate with the return of Donald Trump as president. Among President Trump's first executive orders, is his imposition of tariffs on China, Mexico and Canada. This has exposed China's dominance in the global cobalt market to escalating tariffs and making it a tool in geopolitical disputes.

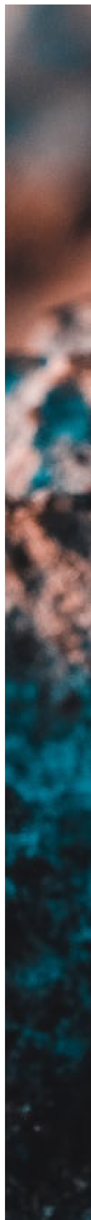
China's dominance in nickel refining further complicates the scenario. Chinese firms control 75% of Indonesia's refining capacity. This gives them a major hold on this key part of the nickel supply chain. By 2030, Indonesia will likely produce 44% of the world's refined nickel. In 2021, China controlled 60% of global production, putting other countries at a great disadvantage. This dominance by China could increase supply chain risks for EV makers that depend on nickel.

The vulnerability of the supply chain of critical minerals is amplified by an assessment that puts all but one of the 17 rare earth elements on a 2022 list of 50 designated "critical minerals", meaning they are economically important yet vulnerable to supply disruption. Furthermore, the limited number of refining facilities for critical minerals, especially outside of China, also constrains resilience.

Sustainable Mining Practices

Obtaining rare earth elements begins with obtaining source materials, which can happen, broadly, in three ways: primary extraction, or mining directly from the earth; recovery from secondary sources, such as end-of-life electronics and batteries recycling; and extraction from unconventional sources, including industrial wastes like coal ash and waste products from mines.

Traditional mining practices are associated with deforestation, habitat destruction, soil



erosion, water pollution, and greenhouse gas emissions. Tailings and acid mine drainage are major hazards, and mining in sensitive areas (e.g., tropical forests or deep sea) amplifies ecological risks. Sustainable mining seeks to reduce these impacts through better technologies, environmental safeguards, and community engagement.

Sustainable mining incorporates environmental, social, and governance (ESG) principles across the lifecycle of a mining project. Key practices include minimising land and water use, reducing emissions and waste, ensuring transparency and traceability, respecting indigenous rights and local communities, rehabilitation and mine closure planning.

International frameworks like the Initiative for Responsible Mining Assurance (IRMA) and towards Sustainable Mining (TSM) provide benchmarks for responsible practices.

New technologies are enabling more sustainable extraction. Some innovative practices that are now commonly utilised include precision mining and automation to reduce waste and emissions, in-situ leaching to avoid surface disturbance, water-efficient and chemical-free processing methods, and blockchain for supply chain traceability. These innovations can lower environmental impacts while improving operational efficiency.

Conclusion

Demand for lithium, cobalt, nickel, and REEs reflects the global clean energy shift. Balanced development that addresses supply, ethical, and environmental challenges is crucial for a just and effective energy transition.

Critical mineral supply chains are inherently geopolitical and vulnerable. Ensuring secure, ethical, and sustainable access to these resources requires coordinated global action, strategic investments, and a commitment to environmental and social governance. Sustainable mining and circular economy strategies are central to building a resilient, low-impact critical mineral supply chain. These approaches offer a pathway to meet climate and development goals while protecting ecosystems and human rights.

The selected case studies illustrate diverse pathways toward critical mineral security, shaped by geography, politics, industry capacity, and environmental standards. Global collaboration, innovation, and inclusive governance will be key to scaling best practices and ensuring equitable access to critical minerals worldwide.

13

CHAPTER 13

CLIMATE RISK INSURANCE AND FINANCING THE ENERGY TRANSITION

Climate change presents multifaceted challenges, including increased frequency and severity of natural disasters, rising sea levels, and shifting weather patterns. These changes pose significant risks to economic stability and societal well-being. Addressing these challenges necessitates a comprehensive approach that includes both mitigation and adaptation strategies. Two critical components in this endeavour are climate risk insurance and financing the energy transition. ▸

Climate risk insurance provides a financial safety net against climate-induced damages, while financing the energy transition involves mobilising capital to shift from fossil fuels to renewable energy sources. This chapter explores the interplay between these components, examining their roles, challenges, and potential in fostering a resilient and sustainable future.

Climate risk insurance encompasses a range of insurance products designed to manage the financial risks associated with climate-related events. These products include traditional indemnity insurance, parametric insurance, catastrophe bonds, disaster relieve funds and contingent credit lines. They aim to provide timely financial support to individuals, businesses, and governments affected by climate-induced disasters, thereby enhancing resilience and facilitating recovery.

Climate risks are broadly categorised into:

- **Physical Risks:** These arise from acute events like hurricanes, floods, and wildfires, as well as chronic changes such as sea-level rise and desertification.
- **Transition Risks:** These stem from the shift towards a low-carbon economy, including policy changes, technological advancements, and market dynamics that can impact asset values, business models and lead to stranded people.

Insurance plays a pivotal role in managing climate risks by:

a) **Risk Transfer:** Distributing the financial burden of climate-related damages across a broader pool, prioritising those that are in a better position to manage it, thereby reducing the risk of materialisation as well as the impact on any single entity.

b) **Risk Assessment:** Utilising data and modelling to evaluate potential climate risks, informing underwriting and pricing strategies.

c) **Incentivising Risk Reduction:** Encouraging policyholders to build green infrastructure, enforce building code as well as land use laws and to adopt risk-reducing measures through premium discounts and coverage terms.

Financing the Energy Transition

The energy sector is a significant contributor to greenhouse gas emissions, necessitating a transition to renewable energy sources to mitigate climate change. This transition involves substantial investments in infrastructure, technology, and innovation. The International Energy Agency (IEA) estimates that achieving net-zero emissions by 2050 requires annual investments of approximately $4 trillion in clean energy technologies. This includes funding for renewable energy projects, energy efficiency improvements, and electrification initiatives.

Financing the energy transition requires climate finance which involves a mix of public and private funding sources, including:

1) **Green Bonds:** Debt instruments earmarked for environmentally friendly projects

2) **Sustainable Investment Funds:** Investment vehicles focusing on companies and projects with positive environmental impacts

3) **Public-Private Partnerships:** Collaborations between government entities and private sector investors to fund large-scale renewable energy projects

There is an interplay between climate risk insurance and energy transition financing. Insurance mechanisms can de-risk renewable energy investments by providing coverage against project-specific risks, such as construction delays, equipment failures, and natural disasters. This risk mitigation enhances the bankability of projects, attracting more investors. Insurance products tailored to emerging technologies, like offshore wind farms and solar energy storage systems, can facilitate innovation by offering financial protection against unforeseen challenges. This support encourages the development and deployment of new renewable energy solutions. Integrating insurance into energy transition strategies ensures that renewable energy infrastructure is resilient to climate impacts. This integration promotes long-term sustainability and reliability of energy systems.

Challenges and Opportunities

Accurate risk assessment for climate-related events and renewable energy projects requires robust data and sophisticated modelling techniques. The lack of historical data for novel technologies poses challenges in underwriting and pricing insurance products. Inconsistent regulatory environments and policy uncertainties can hinder investment in renewable energy and the development of insurance products. Clear, stable, and supportive policies harmonised across regions are essential to foster confidence among investors and insurers and reduce transaction costs. Developing countries often lack the institutional capacity and financial resources to implement effective climate risk insurance schemes and invest in renewable energy. International cooperation and capacity-building initiatives are crucial to addressing these disparities.

Financial Institutions that are involved in Climate Risk mitigation:

African Risk Capacity (ARC) is a specialised agency of the African Union that provides parametric insurance to member states against droughts and other climate-related disasters. By offering timely payouts, ARC enhances the resilience of vulnerable communities and supports food security.

Green Climate Fund (GCF) is a global fund established to support developing countries in their efforts to combat climate change. It finances projects that promote low-emission and climate-resilient development, including renewable energy initiatives and climate risk insurance programmes.

California Wildfires Impact: The January 2025 wildfires in California have led to significant financial repercussions for insurers. Lloyds of London estimates losses up to $2.3 billion, underscoring the escalating risks associated with climate-induced natural disasters. In response to increased climate risks, California approved a 22% hike in homeowner's insurance rates by State Farm. This decision aims to address the financial strains on insurers due to recent catastrophic events.

South Africa's Transition Amid Funding Shifts: Despite geopolitical tensions and changes in international funding commitments, South Africa remains committed to its energy transition from coal to renewables. The European Union has pledged €4.7 billion to support this shift, compensating for funding gaps left by other nations.

The risks and reverberations of climate change are far-reaching, impacting as widely as shareholder claims, parent company and supply chain risk, disclosure investigations and unfortunately much "greenwashing".

The January 2025 California wildfires caused estimated losses of $2.3 billion, highlighting the escalating costs of climate disasters

Such impacts raise the inevitable question of how companies' trusted tools to address and mitigate risk can handle such a systemic global shift. It is important to consider these risks and how an organisation's insurance programme and policies may respond, as well as how climate change is impacting the way insurers underwrite risks.

Even before the dangers of climate change were recognised, mapping an organisation's risk profile and appetite — and evaluating the role of insurance as a mitigation tool — was already a complex task. Such analysis will frequently require input from operational managers, risk managers, insurance brokers and legal advisers, among others. But it is an important exercise, particularly when the risks are evolving. Climate risks come in many guises and unexpected ways for businesses. As well as your own business, it is important to consider the exposures and liabilities of any subsidiaries and others in your supply chain. Existing insurance policies should be considered through a climate lens to ensure they respond as necessary in the event of a claim. Depending on the exposure of a business's value chain to certain risks, new insurance products may need to be considered.

Physical climate risks may be the most obvious. For businesses that own property or land, or rely on others who do, or who rely on the supply of physical resources, there is a potentially increased exposure to physical risks. This is due to the increased severity and frequency of extreme weather events caused by climate change. Such weather events, like flooding, hurricanes and wildfires, can cause enormous amounts of damage to property and resources. Property insurance is the most relevant product here. It is important to consider whether cover for business interruption should also be included and whether there are any exclusions such as pollution which may be relevant.

For sectors where profits are dependent on weather or the availability and use of natural resources or physical materials, parametric insurance may be valuable. Parametric, or index-linked, insurance is where a claim is paid based on a predetermined index, e.g. Richter scale, area yield or rainfall amount. When relevant levels of that index are met, the insurance company should pay out without the need for an actual loss. This can avoid the need for loss assessment, which can consume significant time and resource. Parametric insurance is increasingly used and, if effectively set up, could provide certainty for policyholders and organisations behind them like investors.

Climate disputes fall under the umbrella of climate liability risk. These may be existing risks to businesses that need to be considered through a climate lens – for example, the potential increased liability for board members due to the recent rise in climate litigation. Even if allegations or claims turn out to be unsuccessful, the costs of defending or investigating can be significant and so relevant insurance should be in place.

Directors and Officers insurance (D&O) is potentially the key coverage here and at the centre of emerging climate risks, and ESG more widely. D&O typically responds to claims against directors or officers for actual or alleged acts or errors or omissions committed in their directorial or official capacity. Two key exposures potentially covered by D&O are: shareholder claims (against a company, if the relevant cover is purchased, and individual D&Os) and regulatory enforcement investigations/proceedings arising from matters such as alleged disclosure issues or the way a business is operated. A D&O policy may also typically cover costs incurred in responding to non-routine regulatory investigations into the company's affairs or the conduct of directors or officers.

Professional indemnity insurance (PI) is typically relevant for claims against an insured party for breach of duty in its provision of professional services and costs incurred in responding to regulatory investigations. If climate-related claims allege such a breach, a PI policy may respond but much will hinge on how certain policy terms are defined, e.g., 'professional services' and 'professional loss'.

A feature of a liability policy is that if a third party brings a claim against an insured, the insured must be able to demonstrate to the insurer that it has a legal liability to that third party. That can be complex and difficult (involving issues of limitation and standing of the claimants), especially when publicly defending the claim. Product liability/public liability insurance might also be relevant depending on the nature of the business and the substance of allegations against it1. For example, if products are said to be defective due to alleged contribution to climate change.

Many transition risks may be relatively new, such as preparing for now mandatory climate reporting or the risk of ineffective carbon offsets. Due to the potential gaps in traditional cover, the insurance market is developing solutions by offering new products/services that seek to manage new transition risks and adapt existing insurance. For example, some existing products adapted to expressly provide cover for costs of climate-related investigations.

For the energy transition, insurance products can safeguard the commercial reliability of projects via:

1. **Energy efficiency insurance:** This is specifically designed for investors in energy conservation or financing energy saving projects.
2. **Carbon offset insurance:** One way for companies to try and reach carbon neutrality is to buy carbon offsets, but the voluntary carbon market is unregulated. There is a risk that if the carbon offset scheme does not deliver the anticipated amount of sequestered carbon (for example, trees do not grow as expected, or the captured carbon is lost due to a forest fire) this could leave the offset buyer with risk and liability. This insurance product could cover that risk.
3. **Solar energy/wind product insurance:** If there is a lack of wind or sun, then this product is intended to insure the shortfall.
4. Some of these products are relatively new and it is not clear yet how they may respond in practice. They can also cover the risk of stranded asset resulting from climate policies.

All the risks mentioned above could cause damage to reputation. While there are some specific products available in the insurance market to mitigate this risk, a key part of managing reputational damage is to have the risk management processes and tools installed in the first place. Climate change,

and more widely Environmental, Social, and Governance (ESG), is increasingly important when it comes to obtaining insurance and the underwriting process. The insurance industry's response continues to evolve. There has been a reduction in risk appetite across insurers in relation to emissions-intensive businesses.

Even where climate change might not at first appear relevant to some insurance, at placement or renewal, insurers may ask questions about climate credentials, policies and reporting. In addition, insureds must comply with the duty of fair presentation under the Insurance Act in the United Kingdom (UK). This can affect the amount of cover available and the range of insurers available. Therefore, it is important that risk managers have that information available and have spoken to the relevant stakeholders.

Policyholders with better climate credentials may find they are in a stronger position when buying insurance. Insurers may offer lower premiums, additional capacity and other advantages if certain climate-related requirements are met or if an insured has good climate credentials. On the other hand, insurers may try to influence the conduct of policyholders whose credentials are not as favourable through climate-specific exclusions or higher premiums.

What is Voluntary Carbon Offsetting?

In many countries, including the UK, certain high-emitting industries operate under regulatory carbon markets — such as "cap-and-trade" systems — which impose limits on total emissions and allow trading of allowances. Alongside these mandatory mechanisms, a growing number of companies and individuals participate in voluntary carbon markets, purchasing carbon offsets to compensate for emissions they cannot reduce directly.

These voluntary offsets finance projects that either remove existing carbon dioxide (CO_2) from the atmosphere — such as reforestation or direct air capture — or prevent future emissions, through initiatives like renewable energy deployment or clean cookstove distribution. Many of these projects are validated by independent standards (e.g. Verra, Gold Standard, Global Carbon Council) to ensure transparency and effectiveness.

Companies typically use carbon offsetting to mitigate their environmental impact and as part of demonstrating their ESG credentials and commitment to sustainability. In recent years, offsetting schemes have become an increasingly popular mechanism for companies to try to meet their net-zero targets. A diverse range of companies, spanning from banks and professional service companies to airlines, have invested in such schemes to date. The increase in interest is due to a number of factors, including customer demand and demonstrable levels of ESG compliance being needed to attract investment or finance as well as the increase in mandatory reporting obligations in many jurisdictions in relation to such compliance. In the UK, for example, this is included by regulators such as the Financial Conduct Authority pursuant to obligations under the Companies Act.

One way that companies can seek to offset their emissions is by purchasing voluntary carbon emission reduction credits (VCRs). These VCRs are said to represent how many tonnes of greenhouse gases (GHGs) are being removed from the atmosphere (removal credits), or, in many cases, how many tonnes have been prevented from being emitted in the first place because of the scheme (avoidance credits). The underlying projects can be nature-based (such as forest-related offset projects) or science-based projects (where CO_2 is captured and using various technologies and geological sequestration is used.

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>
> **Günther Thallinger, Allianz**

VCRs are usually registered with an independent third party, which verifies, issues and tracks the VCRs, allows them to be traded and retires them after use or cancels them. Companies can buy or sell VCRs in the voluntary carbon market either directly from a carbon offsetting project or by engaging with a broker or an intermediary. Once a VCR has been purchased and used, the buyer must “retire” it to claim one ton of emission reduction.

How Accurate are the Carbon Reductions?

At present, voluntary carbon offsetting is not subject to any standardised governmental or regulatory oversight. While there are a number of different standards for certifying VCRs (two of the most commonly used being VERRA’s Verified Carbon Standard and the Gold Standard) in recent years there have been suggestions that certain carbon emissions reduction projects may have exaggerated the verifiable levels of emissions reduction.

Determining the exact amount of carbon emissions reduced or avoided by a project can involve intricate calculations. Factors such as baseline emissions (i.e. the emissions that would have occurred without the incentive of the carbon finance), additionality (whether the project would have anyhow happen with or without the incentive of the carbon finance), and leakage (i.e. emissions resulting from the implementation of the project but out of the project boundaries) may contribute to the complexity. The monitoring techniques employed by different carbon offsetting projects to determine the level of emissions reduction vary substantially (perhaps unsurprisingly given the lack of standardised regulation). Such issues can make it difficult for third parties to verify the claimed reductions independently. All these factors contribute to concerns by some about the effectiveness of certain carbon offsetting projects in cancelling out or reducing emissions.

Legal Risks

In this context it is apparent that companies relying on VCRs to balance their emissions face potential legal risks related not only to their use, but also the promotion to investors and consumers of the effect of their use. Indeed, any contract with a provider or broker of VCRs may give rise to disputes if, for example, there is disagreement between the parties as to the "value" of the VCRs, the information to be provided to the customer under the contract or the allocation of funds between stakeholders.

It is possible that companies who promote their use of VCRs to offset emissions may be subject to allegations of greenwashing and the risk of reputational damage as a result. A previous article in this series addressed in broad terms the types of potential greenwashing claims which may arise in different jurisdictions, many of which could potentially arise in connection with the use of VCRs.

Managing the Risks

There are several practical considerations for companies to bear in mind to avoid some of the legal risks described above.

Companies should give careful thought to the claims they are making about their environmental efforts and credentials and whether these claims can be objectively assessed and supported by evidence. They have to use for offsetting VCRs issued by a credible certifying standard, accredited by ICVCM via the Core Carbon Principles, well rated by the Carbon Credit Quality Initiative and complying with the Voluntary Carbon Market Integrity Initiative framework.

Relatedly, when engaging with a carbon offsetting project, it is important to verify the credentials of the project developers and verify the local and global stakeholder consultations to investigate any concerns expressed. Companies may also want to consider the availability and suitability of insurance products which may provide coverage if carbon credits purchased are impaired in some way.

In addition to these practical considerations, there are steps companies can take to seek to mitigate the risks posed by carbon offsetting schemes from a legal perspective.

First, when entering into a carbon offsetting agreement, companies should ensure they are contractually entitled to frequent and specific/comprehensive updates regarding the project in which they have invested. This will provide them with the best opportunity to understand the nature of the project and its impact in terms of carbon reduction. In addition, it is important to ensure the agreement clearly defines the mechanism for credit retirement.

Second, if the scheme involves using the funds paid for VCRs for different purposes, it may be important to enshrine that in the contract (especially if, for example, the credits are being resold by a third-party broker which is taking commission, or if any proportion of revenues is anticipated to be passed to local communities).

Third, companies should consider carefully what contractual warranties and termination rights are required to ensure they have sufficient recourse to damages and/or termination if it transpires that they may not be able to rely on the value of the emissions reductions promised to them in the way originally envisaged.

Fourth, companies should give some thought to the appropriate dispute resolution mechanism in any carbon offsetting contract. They should consider the type of expertise that might be necessary to solve the specific dispute, the forum in which such a dispute should be resolved (bearing in mind both confidentiality concerns and the potential intersection with regulatory issues) and what kind of governing law might be suitable.

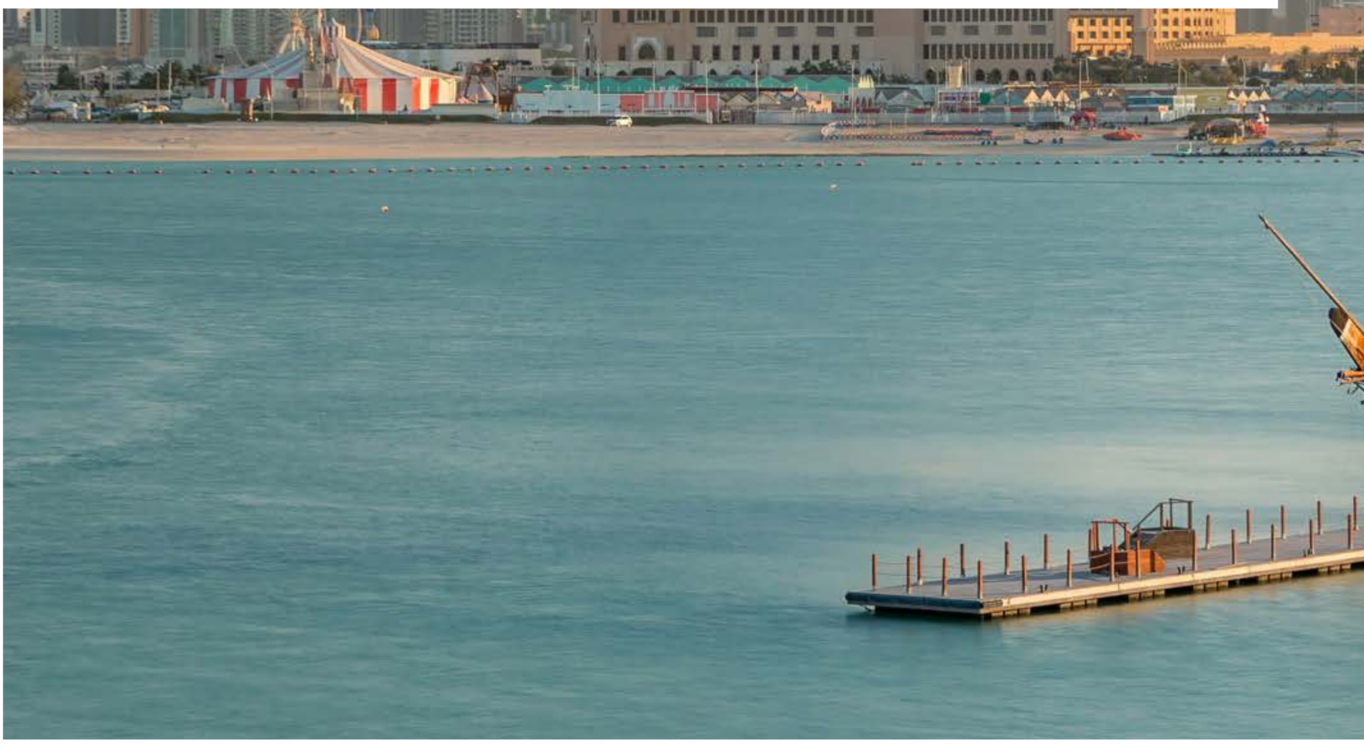
Insurance may be the first system to falter under climate risk. Natural disasters caused $368 billion in 2024 in global economic losses according to Aon (an insurance company). It was the ninth year in a row that losses topped $300 billion. Only 40% of those losses were insured. The protection gap is widening. As insurers retreat from high-risk regions, public safety nets, often overstretched, are stepping in. More households, businesses, and governments are being left to absorb risks they cannot afford. When insurance breaks down, so does credit. When credit dries up, property values fall, costs rise, and resilience weakens, just when it is needed most.

Günther Thallinger, a member of the Board of Management, at Allianz, one of the world's leading insurers and asset managers – put it starkly. "There is no capitalism without functioning financial services. And there are no financial services without the ability to price and manage climate risk." Insurance is often treated as a financial product. But in the climate era, it signals what we're willing to protect, who pays and at what cost. If the signal disappears, the risk doesn't vanish. It shifts onto governments, households, and communities. This is not just market failure, it's a failure of foresight. Resolving this cannot be done with premiums alone.

Conclusion

Climate risk insurance and financing the energy transition are integral components of a comprehensive strategy to address climate change. Insurance mechanisms provide financial protection and incentivise risk reduction, while targeted investments drive the shift towards sustainable energy systems. The synergy between these elements enhances resilience, fosters innovation, and promotes equitable development. Overcoming challenges related to data, policy, and capacity requires concerted efforts from governments, the private sector, and international organisations. By leveraging the strengths of both insurance and finance, societies can navigate the complexities of climate change and build a sustainable future.

As organisations assess their exposure to climate risks and consider updated risk management strategies, considering appropriate insurance should be front and centre. Adequate thought should be given at placement stage and in the event of any climate risk materialising that could rise to an insurance claim. While this article focused on these matters from an English law perspective, similar legal issues arise for companies operating in many other jurisdictions around the world.



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