DNV

WHEN TRUST MATTERS

ENERGY TRANSITION OUTLOOK 2025

A global and regional forecast to 2060

FOREWORD

Ten years have passed since representatives from 196 nations signed the *Paris Agreement*. Since then, only six countries have reduced their emissions in line with their pledges, while the US has exited the Agreement, again. It is now widely acknowledged that the world will not achieve net-zero emissions by 2050. This means warming will exceed 1.5°C and then increase relentlessly until we reduce greenhouse gas emissions to zero.

Faced with these developments, a casual observer might conclude that the energy transition is stalled or in reverse. That is most definitely not the case. The energy transition is rolling on. DNV's annual *Energy Transition Outlook* has, consistently, forecast a shift from today's 80/20 fossil/non-fossil primary energy mix to a 50/50 mix by 2050. That is still our prediction this year, although some aspects of the transition are supercharged and progressing rapidly, while other aspects of the transition have hit turbulence and are delayed. This leads to a marginally slower transition than our forecast last year.

It is now widely acknowledged that the world will not achieve net zero emissions by 2050, which means warming will exceed 1.5°C.

Hydrogen and its derivatives, floating offshore wind, and novel nuclear solutions comprise the expensive side of decarbonization, with uptake driven by policy rather than market forces. These technologies all play a more muted role in this year's forecast, only really scaling in the 2040s.

In contrast, cheap renewable electrons, stored when necessary in ever-cheaper batteries, are already an unstoppable force. We forecast that solar (both with and without storage) and wind will be 32% of the global power mix by 2030. We expect a resurgence in offshore wind by 2030, such that variable renewables will provide more than 50% of all electricity by 2040. By then, electricity will have grown 55% from today's levels. What is stopping runaway developments in electrification is a lagging grid buildout. We estimate that in Europe, absent the present 'gridlock', solar capacity could be 16% higher by 2035, and wind capacity 8% higher.

Soaring power demand from AI data centres is placing additional strain on already congested grids, particularly in North America. Our analysis finds that AI's energy demand growth is likely to become more linear over time (outpaced, for instance, by EV charging demand) even as the cognitive services of AI expand exponentially. That is due to many efficiency effects working together, a theme we explore in some depth in this year's forecast.

In our view, the heightened focus on energy security by policymakers worldwide slightly favours non-fossil over fossil sources in the long run. That includes a resurgence of investment in nuclear power, which we predict will grow 150% from today's levels by 2060. On the fossil side of the mix, policy reversals in the US will see its emission reductions set back around 5 years. The US accounts for one seventh of global primary energy use and thus exerts some influence on the overall picture. However, massive scale decarbonization of the Chinese economy continues, coupled with low-cost electro-technology exports from China to other regions.

This year, our forecast runs to 2060, not 2050. That is mainly because the transition is by no means complete in 2050 and there is a very important dynamic unfolding in the decade thereafter as the world trends further towards a decarbonized energy mix. That trend is unstoppable but too slow, setting up grave risks for future generations.

Net-zero emissions in our forecast is only achieved towards the end of this century, and the accumulation of emissions until then takes us beyond 2°C of warming by 2100. Science has shown beyond any doubt that humanity will then be experiencing, to its great cost, how critical each tenth of a degree of global warming is to our planet and society.

Remi Eriksen
Group President and CEO
DNV

HIGHLIGHTS

1. **Policy reversals in the US will have only a marginal impact on the global energy transition**
2. **Energy security actions globally produce a net result of lower emissions over time**
3. **EV and solar set new milestones as electricity production grows and greens with a progressively higher non-fossil share**
4. **AI's energy use may seem alarming, but at only 3% of global electricity by 2040, is projected to stay below booming sectors like EV charging and space cooling**
5. **Emissions are not even halving by 2050, and urgent action is required to reach the 'well below 2°C' target**

1. Policy reversals in the US will have only a marginal impact on the global energy transition

– This year, we project an energy transition that is marginally slower than the transition we forecast last year, both in terms of emissions and fossil's share of primary energy.

– In the US, fossil fuel promotion and the reversal of clean energy support policies markedly slow that nation's transition. Emission reductions are delayed by about five years (Highlight 1) and through to 2050 annual CO_2 emissions are reset 500 to 1000 Mt higher than we predicted one year ago.

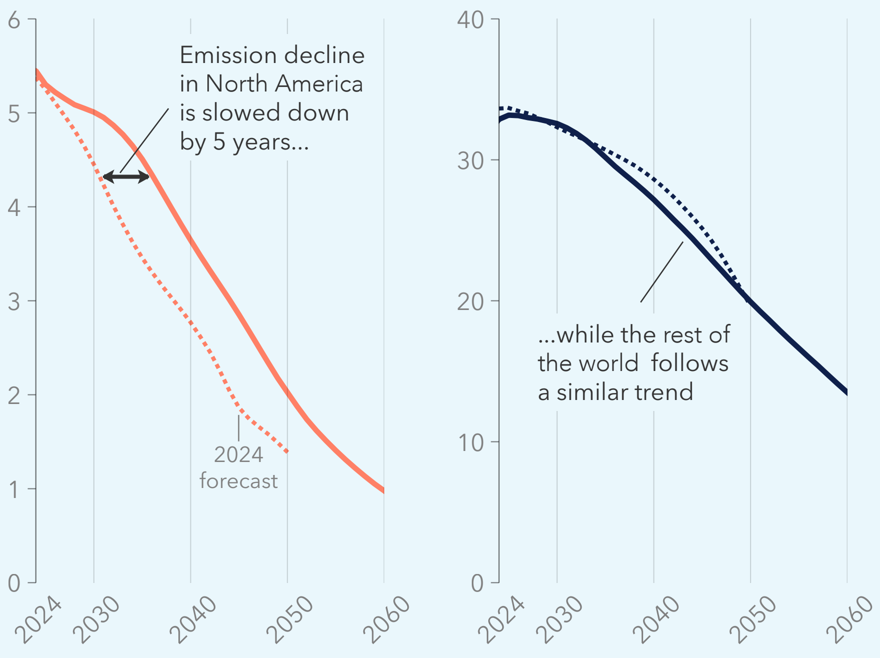
– China continues to set renewables buildout records with 390 GW of solar PV (56% share of new global capacity) and 86 GW of wind (60% share) expected to be installed this year. Chinese cleantech exports continue to propel the transition in the rest of the world.

– Europe is seeking to balance climate action with competitiveness. Harder-to-decarbonize sectors are progressing slowly. While Europe's renewable energy buildout remains relatively strong, it falls short of the EU's 2030 renewable energy targets.

– In the rest of the world, most countries are embracing competitive Chinese technologies, with year-on-year growth in installations at around 25%. Fossil energy use is also rising, but not as quickly. The primary energy fossil fuel share only shrinks from 79% to 75% over the next 10 years.

– This year, DNV forecasts the energy transition to 2060 for the first time. We project the global transition will continue through the 2050s, with acceleration at that time in nuclear and negative emission technologies.

Evolution of energy-related CO_2 emissions in North America and in the rest of the world ($GtCO_2$/yr)



HIGHLIGHT 1 |

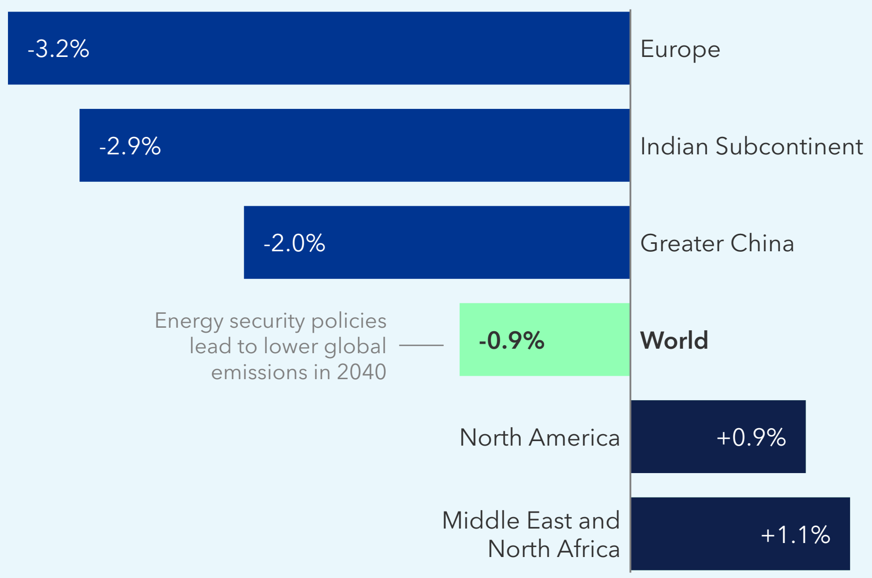
Block Island Wind Farm – the first US offshore wind farm – off Rhode Island. (Photo by Dennis Schroeder / NREL)

HIGHLIGHTS

2. Energy security actions globally produce a net result of lower emissions over time

– Energy security priorities result in a decrease in emissions among energy-importing countries, while energy-exporting countries tend to see an increase in emissions. This trend endures even with the increased emphasis on domestic coal production in China and India.

Effect of energy security policies on energy-related CO_2 emissions in year 2040, in selected regions



HIGHLIGHT 2 |

– When we remove the energy security dimension in our global energy model, leaving only the affordability vs sustainability dilemma, sustainability suffers more. The effects are moderate, but we find energy security actions taken together lower global emissions by a percent or two depending on year. For Europe, the effect is marked: emissions 9% lower in 2050.

– Security-focused governments are pushing nuclear power, and it will account for 9% of electricity supply in 2060. Without the energy security boost, nuclear power would be a third lower.

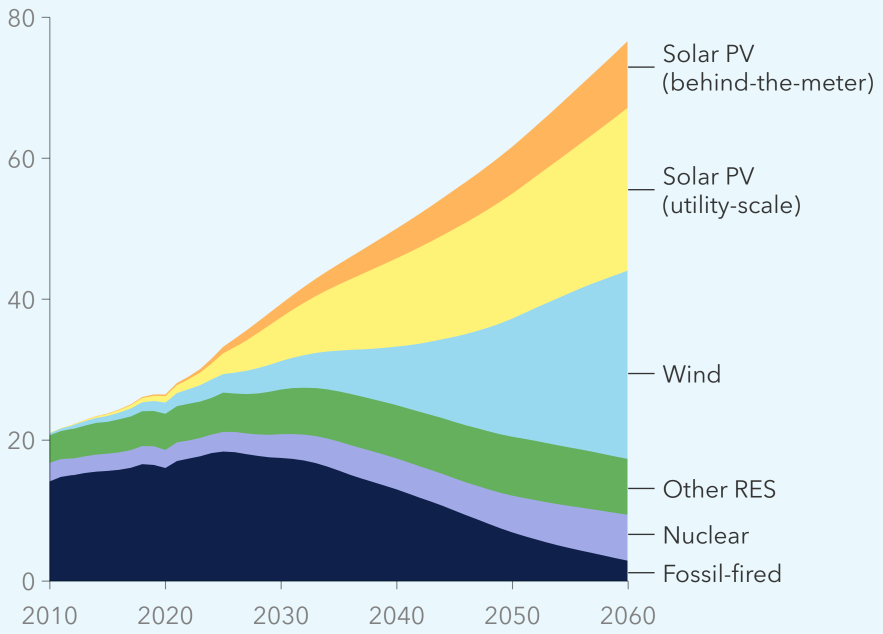
– Energy and national security concerns produce several dilemmas, including varying degrees of willingness to import cheap Chinese technologies.

– Building up effective domestic production, alternative supply chains, and sourcing materials from new sites are all lengthy and expensive exercises, but fully possible. Increasing global tension is weaponizing both energy and energy technologies, with the US and China at the forefront of that race.

3. EV and solar set new milestones as electricity production grows and greens with a progressively higher non-fossil share

– This year, the world reached the milestone of more than 50 million EVs on the road. Most of them (60%) are in China, with Europe at 21%, and North America at 13%. By 2030, we expect there to be 200 million EVs on the road. The point of inflection – EVs at 50% of global new passenger vehicle sales – will be reached in 2032.

World electricity generation by power station type (PWh/yr)



HIGHLIGHT 3 |

– By the end of 2025, global solar PV capacity will exceed 3,000 GW, with 47% installed in China and 20% in Europe as the two leading regions. Rapid growth will continue in all regions: solar PV is 10% of all power produced worldwide today; it will be 20% in 2029 and 40% in 2045.

– The plunging costs of solar panels and batteries have made behind-the-meter (BTM) solutions attractive for a range of households and business. BTM will represent 30% of all solar and 13% of all power generated by 2060.

– Globally, electricity is growing and greening rapidly and at scale. A 120% expansion from today to 2060 will see electricity shift from a 21% share of global energy demand to 43%. This encompasses growth in transport, buildings, and manufacturing in all regions. The fossil share of electricity supply over the same period falls from 59% to just 4%.

– For hard-to-decarbonize sectors, like heavy transport and high heat, we see that global rivalry and the economic slowdown are having an impact. Over the last three years, our forecast for the hydrogen share of the 2050 energy mix has shrunk from 4.8% to 3.5%.

HIGHLIGHTS

4. AI's energy use may seem alarming, but at only 3% of global electricity by 2040, we project it will stay below booming sectors like EV charging and space cooling

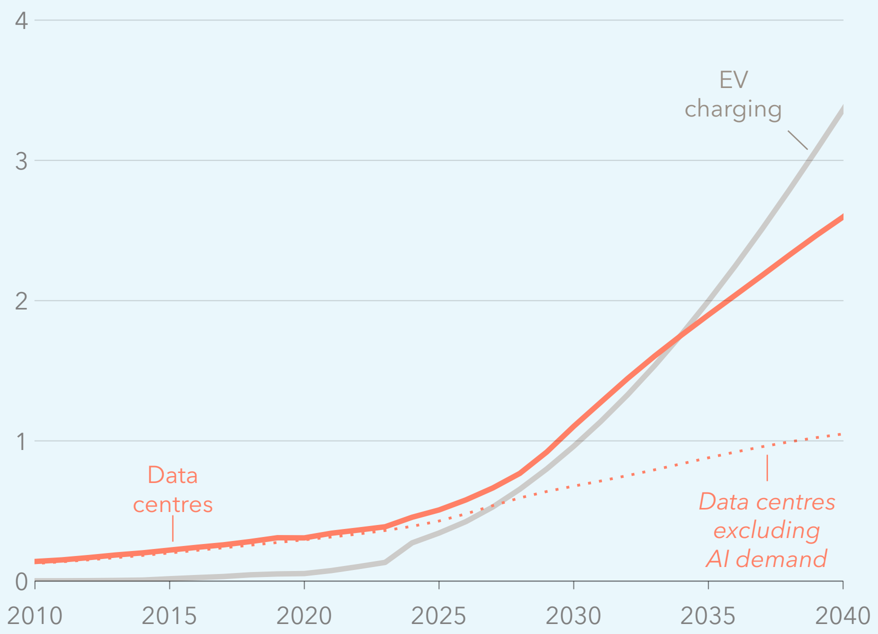
- With power-hungry data centres multiplying to service the rapid growth of AI applications, we find that the initial exponential growth in power demands will give way to a more linear pattern over time.

- Data centre energy use will quintuple to 2040, equalling 5% of all global electricity. 3% of this is for AI and 2% for general-purpose data centres. There are large regional variations; in North America the 2040 share is 16% of all electricity, with 12% being AI.

- Looking at short-term electricity growth, AI is the biggest driver of electricity consumption the next five years in North America. In Europe, EV charging growth far exceeds AI's demand growth, as do both EV charging and the cooling of buildings in China and India.

- The direct involvement of big tech in data centre energy supply is a new driver for new nuclear R&D, in part because big tech is less cost-sensitive than traditional power consumers. However, new nuclear energy will not be ready any time soon, and for the near- to medium-term, additional supply needed by data centres will come from fossil fuels and renewables, with regional variations.

World electricity demand from data centres (PWh/yr)



HIGHLIGHT 4 | World demand for EV charging given for comparison.

5. Emissions are not even halving by 2050, and urgent action is required to reach the 'well below 2°C' target

- Global CO_2 emissions reduce 43% from today to 2050 and 63% to 2060 – and are expected to reach net zero only after 2090. Emissions reduction in both absolute and relative terms is strongest in the power sector with an 88% (13 Gt) decrease, followed by the transport sector with a 58% (5 Gt) reduction.

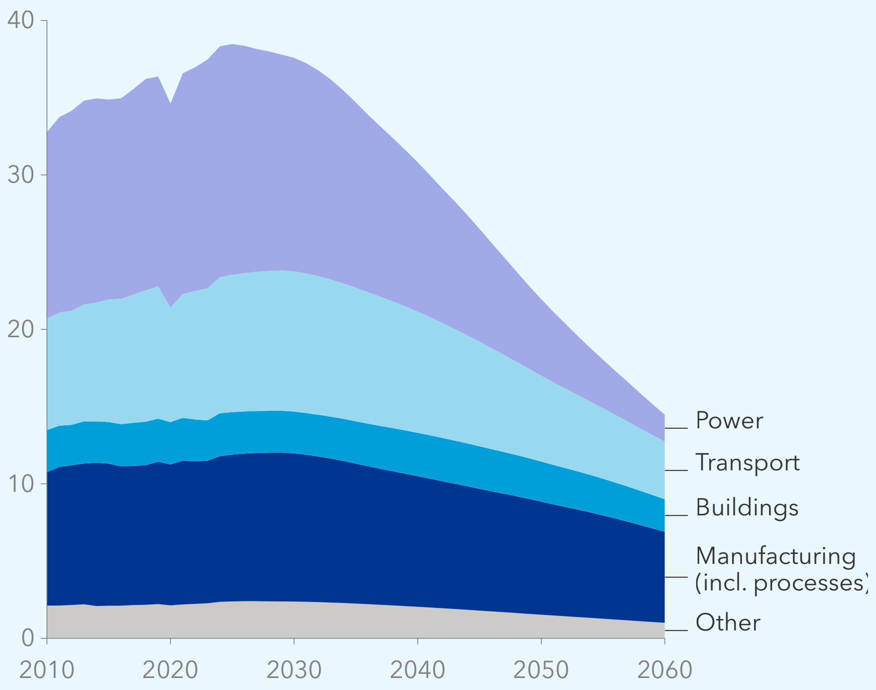
- CCS and net-negative emission technologies remove 35 Gt of emissions from today to 2060, equalling 4% of cumulative emissions in the period. Although the contribution is moderate, CCS is an important part of emissions reduction. Beyond our forecast period, an enormous amount of carbon dioxide removal (CDR) alongside nature-based solutions will be required to ensure net-negative emissions, which we estimate will only occur after 2090.

- The carbon budget for 1.5°C is exhausted in 2029 and 2°C in 2052; limiting global warming to 1.5°C without a temporary overshoot is no longer possible.

- Emissions in our forecast are associated with a temperature rise of 2.2°C above pre-industrial levels by 2100. There is an additional risk of higher warming based on new research on climate sensitivity not yet included in IPCC carbon budgets.

- Limiting global warming to 'well below 2°C' is still possible and urgent actions in all sectors and in all countries and regions are crucial to ensure this.

World CO_2 emissions by sector ($GtCO_2$/yr)



HIGHLIGHT 5 |

CONTENTS

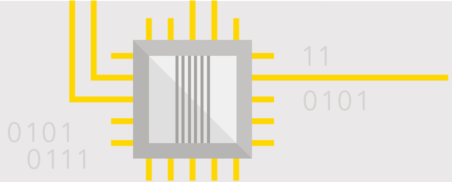
INTRODUCTION

About this Outlook: This is the 9th edition of our annual *Energy Transition Outlook* (ETO), which presents the results of our independent model of the world's energy system. It covers the period through to 2060 and forecasts the energy transition globally and in 10 world regions.

Our **best estimate**, not the future we want

A single forecast, not scenarios

Long-term dynamics, not short-term imbalances



Continued development of proven **technology**, not uncertain breakthroughs

Main **policy** trends included; caution on untested commitments, e.g. NDCs, etc.

Behavioural changes: some assumptions made, e.g. linked to a changing environment

Web resources – www.dnv.com/eto

More detailed descriptions of the regional transitions can be found on our main ETO web hub, along with more specialized reports on the energy transition, country-level reports, and downloadable versions of most of the charts in this and other reports. Our forecast data may be freely accessed at eto.dnv.com/data.

For our readers in maritime and related industries, our annual Maritime Forecast is a widely consulted source on the maritime energy transition.

Our approach

Our guiding principles in producing this forecast include:

- Producing a best estimate of the energy future, which differs in many ways from the future we want to see unfold
- Publishing a single 'most likely' forecast, and not a range of scenarios, which often serve to confuse rather than inform
- Emphasizing and exploring long-term dynamics rather than short-term imbalances
- Focusing on proven technologies and excluding unproven or future potentially 'breakthrough' technologies
- Incorporating main policy trends; treating untested policy commitments with caution
- Modelling effects of behavioural changes – e.g. in relation to energy efficiency.

Chapter 10 contains more details on our modelling methodology and presents an overview of the updates to our model over the last 12 months.

Independent view

DNV was founded 161 years ago to safeguard life, property, and the environment. We are owned by a foundation and are trusted by a wide range of customers to advance the safety and sustainability of their businesses.

70% of our business relates to the production, generation, transmission, and transport of energy. 63% of that work is non-fossil-fuel related and 37% related to the oil and gas industry.

Developing an independent understanding of, and forecasting, the energy transition is of strategic importance to both us and our customers. This Outlook draws on the expertise of over 150 professionals in DNV. In addition, we are very grateful for the assistance provided by external experts. All contributors are listed on the last page of this report.

1 KEY DEVELOPMENTS OVER THE LAST YEAR

1.0 HIGHLIGHTS

Key developments over the last year

Geopolitics and the energy transition

Restructuring the global economy: With geopolitical uncertainty and the IMF's weaker economic outlook, we depart from a 'business as usual' economic forecast for GDP per capita growth.

Geopolitically-driven energy security focus: Governments are increasingly prioritizing domestic energy sources to reduce dependence on imports.

Reshoring manufacturing and regionally-driven technology deployment: Securing access to critical energy infrastructure through domestic manufacturing raises costs in the short to medium term.

Policy debrief

North America is slowing its transition and increasing emissions due to a pivot in US energy policy.

Europe strives to balance industrial competitiveness and climate action.

Greater China is poised for decarbonization leadership, and coal power retraction is starting.

The **Indian Subcontinent** embarks on industrial decarbonization and growing cleantech manufacturing.

Global:

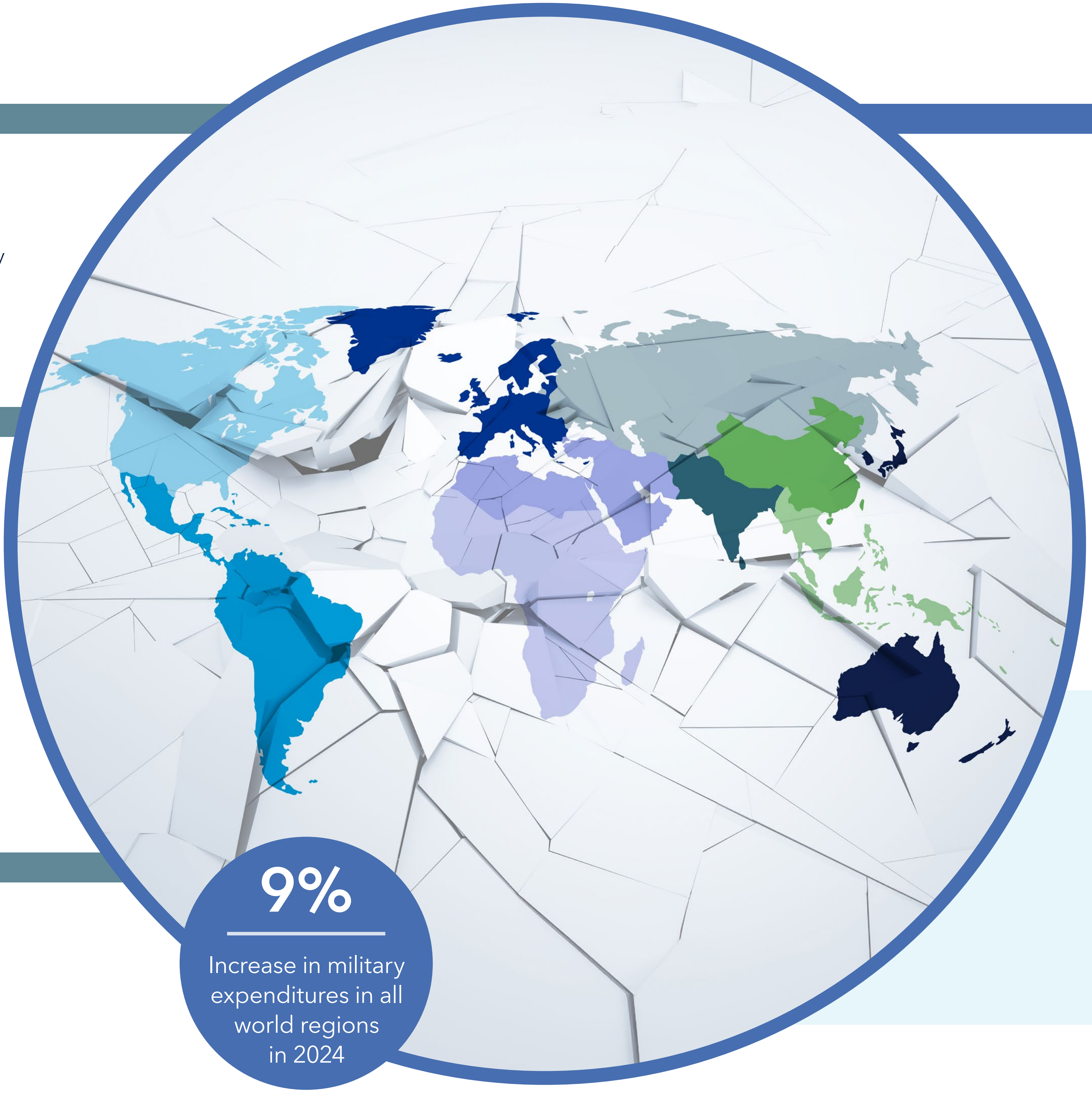
- In April 2025, the International Maritime Organization advanced its *Net-Zero Framework*, set for adoption in October and effective from 2028.
- In November 2024, a *New Collective Quantified Goal* was agreed at COP29 in Baku for a tripling of climate finance.

Other trends affecting the energy transition

Cost declines: China is the undisputed global leader in the production of clean energy technologies, for both domestic use and export.

New producers and consumers: Behind-the-meter solar PV generation (on rooftops and industrial sites) is growing rapidly, making prosumers important players in the power system.

Global warming records: 2024 was the warmest year on record, with an average surface temperature at 1.55°C above pre-industrial levels.



9%

Increase in military expenditures in all world regions in 2024

ETO Model updates

Model sensitivities and improvements

Energy security and policy revisions: Energy security concerns are a defining feature of today's energy landscape. On a global scale, these concerns lead to policies promoting domestic energy sources (both fossil and non-fossil) that collectively tilt slightly in favour of renewables. Our modelling suggests that absent these measures, global emissions in 2040 would have been 0.9% higher.

GDP long-term forecast: Following the IMF and OECD, we have revised our GDP outlook to reflect slower near-term growth and a less optimistic long-term trajectory.

Other adjustments:

Data centres are now modelled with feedback between computing performance, chip supply, and server costs, with separate treatment for AI-focused facilities.

Behind-the-meter solar and storage are captured in more detail.

Carbon pricing is represented more dynamically, rising not only with absolute emissions, but also with the pace of decarbonization, strengthening the link between policy ambition and progress.

2060 forecast

For the first time, we are modelling to 2060, not 2050.

Although the energy system of 2050 will be significantly different from today, the world will still be in the middle of a transition.

Many national decarbonization plans set a net-zero emissions target date closer to 2060.

1.1 GEOPOLITICS AND THE ENERGY TRANSITION

The current geopolitical landscape is shaped by two overlapping confrontations between superpowers. A systemic US-China competition has expanded from trade to encompass technology, finance, and security, with intensifying export controls and investment screening across sectors. Russia's war against Ukraine has entrenched a military standoff with NATO and accelerated rearmament, causing defence spending and industrial mobilization to rise in Europe and Asia. Together, these dynamics constitute a renewed arms race spanning conventional forces, missile defences, space, and cyber, reinforced by tightening minilateral coalitions and counter-coalitions.

Globalization is fragmenting rather than reversing. Sanctions, tariff expansions, industrial policy, and critical-minerals and data-localization rules are re-wiring supply chains toward 're-/friend-shoring'. Recurrent trade shocks – including the pandemic, the Suez and Panama Canal disruptions, and the Red Sea shipping attacks – have reinforced a shift from efficiency to resilience, duplicating capacity and raising costs. Confidence in rules-based governance is weakening; the WTO's dispute settlement system remains paralysed and Security Council vetoes have constrained UN action on major conflicts. The result is a more transactional order characterized by selective interdependence, contested agreements, and thinner trust in multilateral guarantees.

Our geopolitics considerations in this forecast focus on the ways states and regions leverage resources, infrastructure, and technologies to advance national security, economic interests, and influence within the global energy system. To determine the effect of geopolitics on the energy transition and reflect the changing geopolitical landscape, we included and updated critical factors such as GDP development, added costs for energy security, the expense of reshoring manufacturing, and a reduction in trade. We evaluate the tension between the push for energy independence (which often favours renewables) and the push for homegrown clean technology supply chains that threatens to raise costs and further fragment global collaboration and trade. Recent policy decisions and sentiments have shifted in key economies (see Section 1.2 for more details).

We explore the tension between the push for domestic renewables and the expense of homegrown clean tech supply chains.

The net effect of today's geopolitics is a transition driven by a 'security-first' mindset. We observe continued deployment momentum in sectors where costs are lowest (solar, storage, onshore wind) and displace fossil imports, and where energy sources align with security (such as nuclear extensions and newbuilds). In these areas, global progress continues and the transition is hardly slowing compared with last year's forecast. While the US policy pivot does create a transition setback in North America, the impact on the global transition is marginal. In fact, the net effect of energy security-driven prioritization of national energy sources is slightly lower global emissions over the long term. However, this upside is not sufficient to achieve climate goals (see Chapter 8 for more details). Our 'most likely' future sees net-zero emissions only achieved in the 2090s, and we expect global temperatures to reach around 2.2°C above the pre-industrial average by the end of the century.

> The net effect of energy security-driven prioritization of national energy sources is slightly lower emissions in the long term.

Incorporating geopolitical trends into the forecast

The geopolitical changes and energy security situation have a direct impact on the energy transition and our modelling. We have incorporated a modest restructuring of the global economy, with geopolitically-driven economic security considerations reflected in technology development and reshoring manufacturing, and a modest change in the future demand for global trade.

Restructuring of the global economy – GDP per capita

Given today's geopolitical uncertainty, we depart from a 'business as usual' economic forecast for GDP per capita growth. For short-term projections, we use the IMF's weaker economic outlook (IMF, 2025). Long term, we draw on GDP data from OECD and the International Institute for Applied Systems Analysis (IIASA), which point to a slower economic trajectory that reflects a world where economic nationalism, weak institutions, and lack of coordination cause economic stagnation and deepening global inequality (see Chapter 10 for more details and references on GDP). Broadly speaking, nations are likely to prioritize security and self-sufficiency over global trade and sustainability. Economic development and industrial sector shifts are thus slower and more uneven, especially in poorer countries.

Prioritizing domestic sources for energy security

Governments are increasingly prioritizing domestic energy sources to reduce import dependence, build immunity to supply disruptions, and mitigate the risk of energy being used as a geopolitical weapon. This shift means that energy resources may be penalized or deprioritized despite favourable short-term economics, with choices shaped by domestic resource availability, technological capacity, and workforce skills. Energy security considerations, especially in the power sector, can thus support both low-carbon and fossil options: Europe, for example, leans toward nuclear and renewables; China favours renewables, nuclear, and coal; and North America, at least for now, wants to boost oil and gas output. Our power model reflects these dynamics by incorporating regional policy support levels that capture both current priorities and likely future trends.

Technology deployment and reshoring of manufacturing

Our assessment of nuclear deployment assumes that adoption and use are 'bloc constrained'. North America, Europe, Japan, and South Korea will not adopt nuclear from Russia or China, and vice versa, while we assume that other regions will source evenly from both blocs. This constraint diminishes learning curve effects in future cost trajectories and shapes developments and costs in supply chains for spare parts and fuel.

For the largest import markets of green technology in Europe and North America, recent policy decisions like tariffs, domestic content rules, state aid, and credit refunds tied to local production are boosting alternative supply chains, such as local solar panel production, but success remains fragile. Our model represents reshoring of energy technology manufacturing as a reduction in learning rates of between 10% and 40% for solar, wind (onshore and offshore), and Li-ion batteries in Europe and North America. This reflects both scale and experience disadvantages. Thus, we see learning rates decline as the industry builds up, with the cost impact starting from 2024, peaking in 2030, and then gradually returning to global averages by 2045. While these measures create temporary regional cost pressures, their effect on global technology costs and the overall trajectory of the energy transition remains marginal.

Demand for maritime trade

Recent conflicts, like the war in Ukraine and Houthi attacks, have disrupted trade patterns, leading to increased shipping distances, for example, Russian oil and the re-routing of shipping lines to avoid the Red Sea. An additional uncertainty for global maritime trade has now arisen in the form of the expansion of trade tariffs by the US, which further fuels the trend towards re-/friend-shoring and supplier diversification. To reflect this shift in uncertainty and changes in supply chains, we have implemented a slight reduction in container, bulk, and other cargo trade, starting in 2025 that results in a global 5 to 10% overall reduction of trade in these segments by 2040.

1.2 POLICY DEBRIEF

Political uncertainty in the current geopolitical environment is a pressing challenge for the transition. Despite 2025 marking the 10th anniversary of the *Paris Agreement*, climate action is no longer a top priority for many governments and clean energy still progresses unevenly across regions and sectors. While annual investments in renewable power and related electro technology continues to rise, energy and climate policies are now closely tied to strategies for future-proofing both energy sectors and regions against geopolitical risks. In the pursuit of economic sovereignty, many countries are slowing imports to protect domestic industries, making their transitions more complex and expensive.

DNV observes five key trends framing policy and the transition in 2025:

1. Flux in the rules-based, liberal international order is creating economic and policy uncertainty. Amid rising geopolitical tension and superpower rivalry, free trade can no longer be reasonably expected. This results in global market segmentation. Trade risks, such as tariff escalations, export and investment controls, and prohibitions in rules of origin, are forcing a rethink of materials and cleantech supply chain strategies. Trade route disruption is contributing to volatility in commodity prices and raising concerns about the security of supply for fossil fuel importers.

2. New modes of climate collaboration are emerging as global cooperation stumbles. 'Minilateralism', for example, involves smaller groups of nations and corporations cooperating through focused initiatives to tailor solutions to specific shared challenges (Mladenov, 2023). Club-based approaches (Budak, 2025) – like the Climate Club for industrial decarbonization, the Carbon Management Challenge to advance CCS, and the Green Shipping Corridor and Zero Emission Maritime Buyers Alliance – drive collective action to develop bespoke solutions and generate deployment momentum.

3. The pursuit of local benefits and domestic cleantech industry has strong political staying power, driven by national security, economic resilience, and the desire to reduce reliance on global supply chains. Industrial policy with local content and localization rules aims to capture more value domestically, but adds complexity to energy projects. Policymakers must balance these goals with affordability for households and business competitiveness. Ensuring fair distribution of both benefits and burdens across communities and the economy is essential for public support and policy success (Chapter 6).

4. Tension and conflicts, where energy infrastructure is increasingly targeted, are driving up military spending and diverting public funds away from environmental policy, aid, and GHG emissions reduction (CEOBS, 2025). Military expenditures, increasing in all world regions, rose by over 9% in 2024 to reach USD 2.7trn, the steepest year-on-year rise since the end of the cold war (SIPRI, 2025).

5. The consequences of global warming continue to put pressure on governments to prioritize climate action. 2024 was the second consecutive hottest year on record, and the first to exceed 1.5°C above the pre-industrial average (WMO, 2025a). Climate-related disasters are causing massive losses, with Swiss Re estimating insured damages at USD 145bn in 2025, up 6% from 2024 (Munich Re, 2025; Swiss Re, 2025). The recent International Court of Justice opinion on state responsibilities to prevent climate harm suggests that legal risks will be rising (ICJ, 2025).

Key global and regional developments

Key global developments

At COP29 in Baku, countries agreed to triple climate finance from developed to developing countries, setting a *New Collective Quantified Goal* (NCQG) of USD 300bn annually by 2035. Access to finance to catalyse clean energy investments and climate adaptation, especially in low-income regions, underpins new nationally determined contributions (NDCs) to 2035. However, a 7% drop in international aid in 2024 (OECD, 2025), including cuts to USAID's Power Africa, threatens progress and energy finance.

The International Maritime Organization advanced its 2023 GHG Strategy with a Net-Zero Framework approved at MEPC 83 in April 2025, set for adoption in October and effective from 2028. Targeting ships over 5,000 Gt, the framework aims for net-zero emissions by 2050. It introduces a technology-neutral approach, including a well-to-wake fuel standard (GHG fuel intensity and reduction requirement) and carbon pricing. Revenue will fund a Climate Fund for green technologies and fuels (IMO, 2025; DNV, 2025).

Key policy developments in select ETO regions

Europe

Strives to balance industrial competitiveness and climate action

- The EU Commission proposed a 90% GHG reduction target by 2040 that includes flexibility – up to 3% via international credits from 2036 and domestic removals integrated into the EU ETS (EC, 2025a). However, reservations from major member states and parliament have delayed decision making and the EU's joint updated nationally determined contribution (Genovese, 2025).
- Building on the *Letta* and *Draghi* reports, the EU launched the *Clean Industrial Deal* (Feb 2025) to align industrial policy with the *Net-Zero Industry Act* and strengthen domestic cleantech industry; and the *Automotive Industrial Action Plan* (March 2025) which backs battery manufacturing, trade defence, and cybersecurity (EC, 2025b). The *Clean Industrial Deal State Aid Framework* (June 2025) allows public support in line with cleantech, energy, and decarbonization objectives, including electricity price relief for energy-intensive industries (EC, 2025c).
- The *Omnibus package* streamlines regulation, easing the *Carbon Border Adjustment Mechanism* rules, but still covers 99% of emissions from key sectors (EC, 2025d).

North America

Pivot in US energy policy is slowing the region's transition and increasing emissions

- The US has exited the *Paris Agreement*, instead prioritizing fossil-fuel expansion, and has rolled back environmental rules, including those related to vehicle emissions, industrial standards, and power plant air-pollution control (EPA, 2025). Executive orders now require fossil-fuelled power plants slated for closure to remain operational and revoke state-level climate laws (White House, 2025; Forbes, 2025). 24 US states in the US Climate Alliance remain committed to climate goals (Segal, 2025).
- The *One Big Beautiful Bill Act* modifies and/or repeals several *Inflation Reduction Act* (IRA) tax credits, including those for clean energy, EVs, home energy efficiency, and clean hydrogen. The bill ties credit eligibility to construction start dates and materials and rescinds unspent funds from the Department of Energy's loan programmes.
- Canada largely shows continuity in climate and low-carbon energy policy. Its new NDC targets a 45 to 50% GHG reduction below 2005 levels by 2035 (Government of Canada, 2025) and deepens ties with the EU (PM of Canda, 2025) on energy, minerals, and global challenges.

Greater China

Poised for decarbonization leadership but coal power capacity additions continue

- China reaffirmed its *Paris Agreement* commitment and maintains momentum on climate action. Its updated NDCs will cover all economic sectors and all GHGs (Government of China, 2025a). September 24. 2025, President Xi Jinping announced a 7 to 10% reduction by 2035 from peak levels (China Daily, 2025).
- Carbon pricing expands to align with the country's dual carbon targets (Government of China, 2025b) to include steel, cement, and aluminium smelting industries in the national ETS by 2025, and all industries and aviation by 2027 (MEE, 2025; Qin, 2025).
- The continued growth in coal power buildout in 2024 (CREA, 2025) underscores coal's role in energy security, but creates uncertainty in coal phase down goals (*15th Five-Year Plan*) and seemingly contradicts the government's stated goal to curb coal use during the *14th Five-Year Plan*.
- China is shifting cleantech exports to emerging markets, rising to 43% in 2024 (Mooney et al., 2025). The *Belt and Road Initiative* is boosting renewable and fossil-fuel engagements (Nedopil, 2025).

Indian Subcontinent

Embarks on industrial decarbonization and growing cleantech manufacturing

- India, the region's largest economy, plans a carbon capture mission (Anand, 2024), and its 2026 *Carbon Credit Trading Scheme* aims for emission intensity reduction in nine industrial sectors.
- The *Union Budget 2025-26* launches the National Manufacturing Mission to boost domestic cleantech and seemingly reduce technology import dependence on China (Government of India, 2025). Energy transition investment rose 13% to USD 47bn in 2024 (BNEF, 2025).
- The *Union Budget 2025-26* includes a 100 GW of nuclear capacity target by 2047 for energy independence.

Further details on the Outlook's ten world regions are available here

1.3 OTHER ENERGY TRENDS

Falling technology costs, new consumers and producers, AI, and global warming records are just some of the other macro trends that have influenced the energy industry over the last 12 months.

Technology cost declines

China's systematic pursuit of mining and processing critical metals and minerals has granted them dominance over global supply chains and the ability to weaponize rare earths at will. In addition, China continues to drive cost advantages through industrialization, mass production, and concessional finance and real estate. Ever-cheaper Chinese technologies are available all over the world and, absent tariffs and other trade barriers, make solar PV, onshore wind, and EVs ever more competitive. Solar and wind are already the least expensive form of new electricity in most parts of the world, and EV sales, now approaching one fifth of passenger vehicle sales globally, are increasingly competitive with combustion vehicles.

However, these plunging costs are limited to solar, onshore wind, and batteries. In traditional energy industries (e.g. oil and gas), AI might have a significant potential to reduce exploration, production, and logistics costs, but increases in supply may result in a net negative for prices. In less mature technologies like offshore wind, hydrogen, nuclear small modular reactors (SMR), and CCS, cost reductions over the last year have not matched those in solar and batteries. Despite its relatively high costs, there is increased focus on nuclear because it can offer energy security and may have a role in powering data centres.

New producers and consumers

Behind-the-meter (BTM) solar PV generation is growing rapidly, both on rooftops and industrial sites, making prosumers important players in the power system. The growth of BTM with solar+storage is even more rapid, enabling households and businesses to capture surplus solar production, avoid curtailment, and shift consumption to periods when grid electricity prices are higher. Presently, about one third of all solar installed globally is BTM.

We describe our modelling on BTM in detail in Chapter 3 where we also deep dive into AI and data centres, which are attracting attention on the demand side of the energy equation.

Although net growth in data centre energy demand globally is smaller than growth in cooling and EV charging, it is bigger and more headline-grabbing in North America because of the hype surrounding AI. Data centre operators are theoretically able to pay significantly more for their power than traditional consumers. Indeed, a number of big tech players are actively investing in nuclear R&D, with SMR as the first goal and fusion as a more distant goal, as a cleaner energy alterative to new gas turbines where wait times are becoming increasingly unattractive, even before the additional cost of CCS (Patel, 2025).

AI developers also promise to revolutionize the energy system with everything from grid balancing to autonomous driving and manufacturing. However, we are at the advent of this change, and the range, pace, and consequence of AI's impact on the energy system remains unclear (see Chapter 2 for further discussion).

New global warming highs

2024 was the warmest year on record, with a global average surface temperature of 1.55°C above pre-industrial levels (WMO, 2025b). With sea surface temperatures in the equatorial Pacific currently trending away from El Niño to more neutral or La Niña conditions, 2025 will not be as warm as 2024 but will be among the five warmest years of the last decade. Climate change-related extreme weather events have continued over the last year, with monsoons, heatwaves, and fires devastating all continents. This is not yet galvanizing significant policy or behavioural change at a global level. Accordingly, we forecast global warming of 2.2°C at the end of this century, unchanged from our 2024 estimate.

Updates to key parameters

In addition to updating the ETO Model to reflect geopolitical shifts, we have updated several other parameters. Some of these are related to geopolitics, but many also reflect a broader set of developments over the past year, particularly domestic policy actions. (See Chapter 6 for extensive coverage of carbon prices and supply side policy support, and Chapter 7 for a discussion of cost of capital developments).

Carbon Prices – We now find that carbon price increases will be significantly slower than previously forecast.

Renewable and green support schemes and subsidies – Most OECD countries continue with extensive supply-side policy actions: funding R&D, technology, and green supply chains, infrastructure investments, auctions, and contracts for differences for renewable power. However, the US energy policy reversal has seen cuts to grants and loan programmes for clean energy development. We also observe a continuation of hydrogen and CCS project support, but the development is evolving more slowly than targets require.

Cost of capital – Capital-intensive technologies reliant on subsidies – such as floating offshore wind, hydrogen, and CCS – face a growing risk of waning policy support. Increased spending on defence diverts resources from decarbonization, while shifting risk perceptions drive up the cost of capital. This further increases subsidy needs and reinforces a negative spiral.

1.4 UPDATES TO THE MODEL

Energy security and policy revisions

The resurgence of energy security concerns has become a defining feature of today's energy landscape. Governments are framing policy primarily around control over resources and technologies, with climate and cost seemingly lesser concerns. This has reshaped subsidies, redirected investment, and, in some cases, slowed renewables. In the US, security arguments have led to deregulation of both fossil fuel production and nuclear, although that has yet to translate into significant new capacity, and there is debate as to whether it will. In Europe, China, and the Indian Subcontinent, the same concern has reinforced investment in and supportive policies for renewables, nuclear, and CCS as ways to reduce dependence on imports.

In our model, the net effect of energy security concerns falls slightly in favour of renewable energy in the long term (Figure 1.1). Without energy security measures, global emissions in 2040 would have been 0.9% higher than we forecast. For importers such as Europe, India, and China, security-driven support for low-carbon supply keeps emissions lower than they otherwise would be. For exporters such as the Middle East and North America, the reverse is true: energy security has often meant prioritizing domestic fossil production. Overall, energy security actions tilt in favour of lower emissions, largely because the final energy demand footprint of the 'non-fossil security' group is bigger than that of the 'fossil security' group.

GDP scenario revisions

Economic prospects shape the transition because they determine both the scale of energy demand and the resources available to finance it. We have revised our GDP outlook to reflect slower near-term growth, following the IMF and OECD, and a less optimistic long-term trajectory. Instead of a single central pathway, we now use an average of SSP2 and SSP3 (see Section 10.5 for more details on population data in our model). This reflects our judgement that while global cooperation remains possible, the likelihood of weaker institutions and fragmented trade has increased. Put simply, the world is less certain to continue along past growth patterns.

In our counterfactual analysis, the revised GDP pathway results in 6.3% lower emissions in 2050 compared with a pure SSP2 case (Figure 1.2). Slower convergence between rich and poor regions also means energy demand, along with emissions, grows more slowly in low-income countries. The revision therefore carries a double message: the energy system may face less pressure from demand growth, but the social challenge of uneven development becomes sharper (see Chapter 10 for full details of our GDP projections and their assumptions).

Model improvements

The third set of changes reflects areas of the energy system that have grown too important to simplify.

Data centres are now modelled with feedbacks between computing performance, chip supply, and server costs, with separate treatment for AI-focused facilities. Their rapid growth makes them a structural driver of electricity demand rather than a marginal load. **Behind-the-meter solar and storage** is captured in more detail, accounting for how households and firms balance costs, incentives, and reliability when investing in new systems.

Carbon pricing is represented more dynamically, rising not only with absolute emissions but also with the pace of decarbonization, strengthening the link between policy ambition and progress. **Grid constraints** are explicitly modelled, reflecting how transformer availability and rollout of grid newbuild capacity can slow electrification. **CCS and carbon dioxide removal** are now integrated with wider applications, updated cost assumptions and explicit infrastructure needs. Together, these refinements show how technological, economic, and policy factors interact to allow the model to better capture the dynamics that will shape the transition (see Chapter 10 for a full list of updates).

Energy security policies lead to lower global emissions
Effect of energy security policies on emissions in year 2040

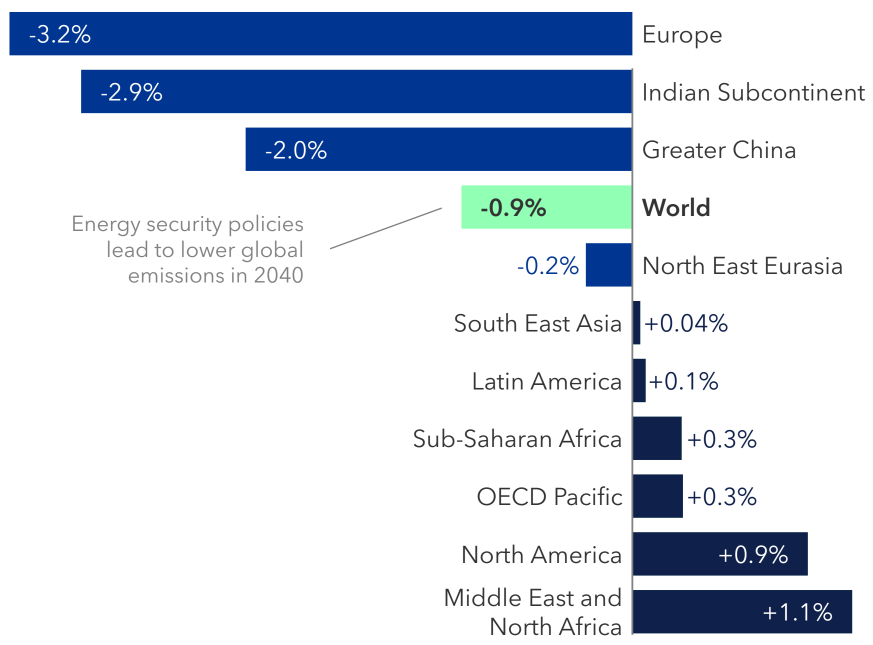


FIGURE 1.1 | Effect on energy-related emissions.

The uneven impact of changing our GDP scenario
Relative difference with a pure SSP2 scenario

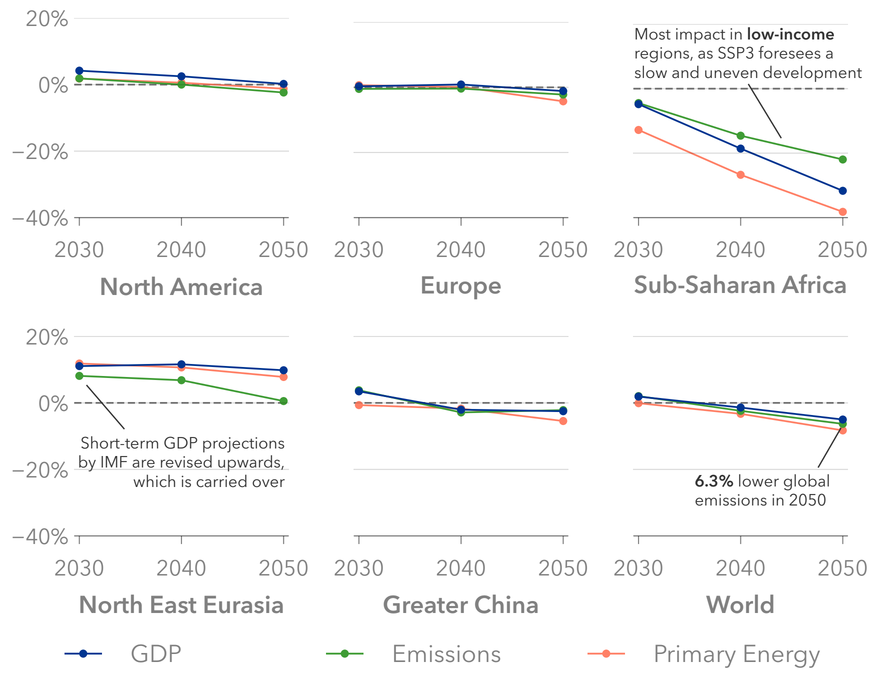


FIGURE 1.2 |

1.5 FORECASTING TO 2060

Our *Energy Transition Outlook* this year gives the full forecast to 2060 instead of 2050. 2050 is just 25 years away, and while the energy system will have changed greatly by then, it will still be transitioning.

There are two other arguments for looking beyond 2050. First, many national climate and emissions pledges look beyond 2050; comparing our forecast with those pledges would not be possible if we did not extend our forecast horizon. Second, we state for the first time this year that we find net-zero CO_2 emissions in 2050 are beyond reach and looking at what happens after 2050 is therefore even more relevant (see Chapter 7 for a detailed discussion).

Many of the energy assets constructed today will have a lifetime beyond 2050, some possibly beyond 2060. However, 2060 represents the limit to which we are willing to take our forecast before uncertainties detract from the quality and usefulness of detailed modelling.

Some of the uncertainties in forecasting to 2060 include the following:

The 2050s will see huge developments in hydrogen and its derivatives, nuclear power, and carbon capture
Evolution of key energy indicators, 2050–2060

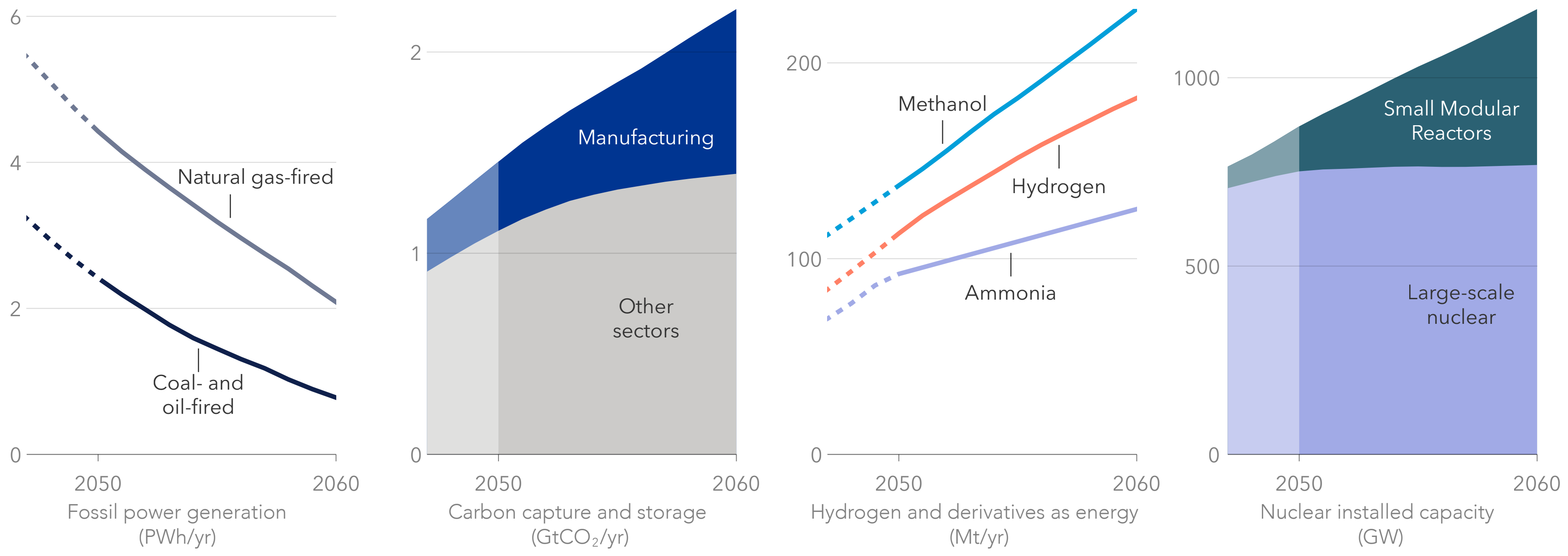


FIGURE 1.3 | Hydrogen and derivatives as energy from electrolysis-based and fossil-based with CCS production routes.

- **Population:** Unlike other parameters, population forecasts have moderate to low uncertainty in this time horizon, and a change in the declining fertility trend seems unlikely.
- **Economy:** There are intense debates on whether AI will dramatically change economic growth models, which part of our economy it will influence most, and how various countries will gain or lose. More generally, the longstanding divide between high-, middle-, and low-income countries is likely to endure.
- **Technology:** The electrification trend is certain and will remain. Breakthrough technologies, especially digital ones like AI and quantum computing, are more likely to transform our energy system by 2060 than by 2050. Nuclear is an area with significant uncertainty, and fusion and novel nuclear have a huge potential impact, but are at the tail end of probability.
- **Policy:** Policy uncertainty is already high on the 2050 horizon and can shift overnight with changes of regimes. The uncertainty persists towards 2060, but does not grow exponentially.
- **Behavioural change:** This factor has large potential, but has a low impact on our forecast since we anticipate little change in behavioural patterns or voter preferences. Towards 2060, the uncertainty increases in areas like work patterns, sharing economy behaviour, and in reactions to the effects of intensifying climate change.

The system dynamics methodology used in the ETO is suitable for modelling the interaction and feedback loops between the various parameters. Our model runs all the way to 2100, and we use these results for the emissions and climate part of our forecast. For the full forecast however, we restrict our detailed commentary to 2060.

Is the 2060 energy system more stable than the one of 2050? In some ways, it is more settled. By 2060, fossil fuels will have almost disappeared from our electricity system and internal combustion engine vehicles will hardly feature in passenger and commercial vehicle sales. That part of the transition will effectively be 'over'. In other areas, like the aviation fuel mix and phase out of natural gas boilers and stoves, rapid developments will still be taking place in 2060 and the energy transition will still be in mid-stride.

In 2050, the energy transition will still be in mid-stride, with many further important changes unfolding in the decade to 2060.

2 DNV FORECAST

2.1 SUMMARY OF ENERGY SUPPLY AND DEMAND

Renewables replace fossil energy

- Renewable uptake will be driven by solar and wind. From 3% today, they will provide more than a third of primary energy supply by 2060.
- The growth in solar and wind, combined with other sources like nuclear or hydropower, will lead to non-fossil energy dominating from the 2050s.
- Fossil energy has provided a constant 80% share of primary energy for the past few decades. That pattern is now breaking. Primary energy supply will start to level off from the 2030s, while non-fossil steadily displaces fossil energy in primary energy mix.

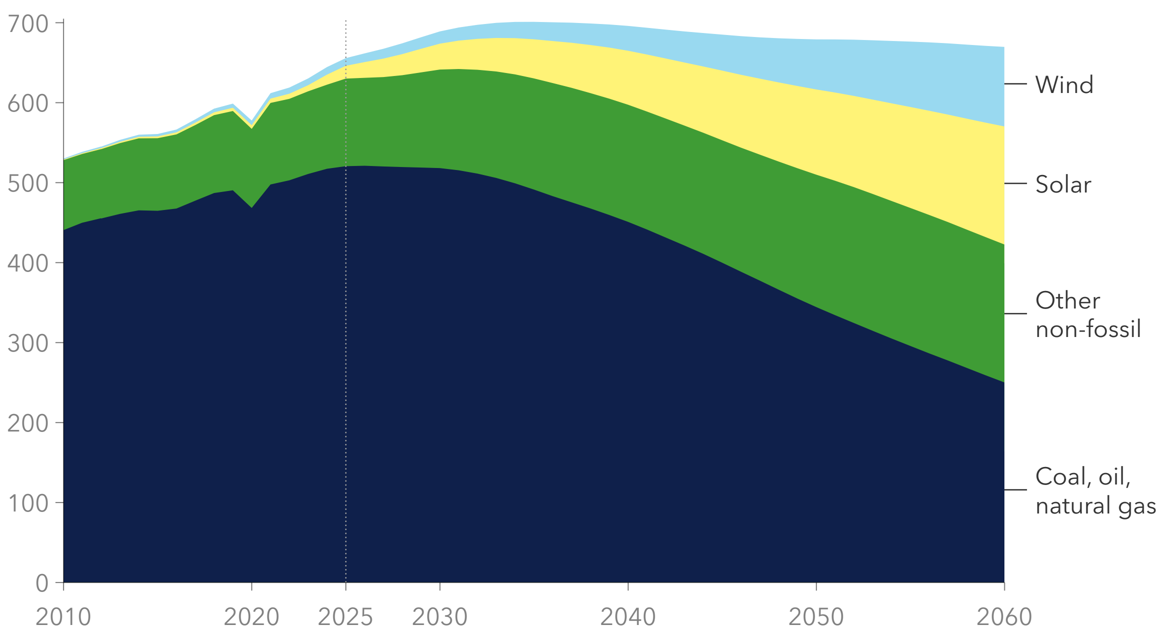
Rapid electrification

- Decarbonization goals, spurred by cheap renewable electricity, will see electricity demand more than double by 2060.
- As final energy demand plateaus, electricity will push fossil fuels out of the mix.
- Electricity will also be used to produce hydrogen and its derivatives for the indirect electrification of hard-to-decarbonize sectors like high-heat applications and heavy transport. Hydrogen and its derivatives will cover 1% of energy demand by 2040 and 6% by 2060.

More efficient energy systems

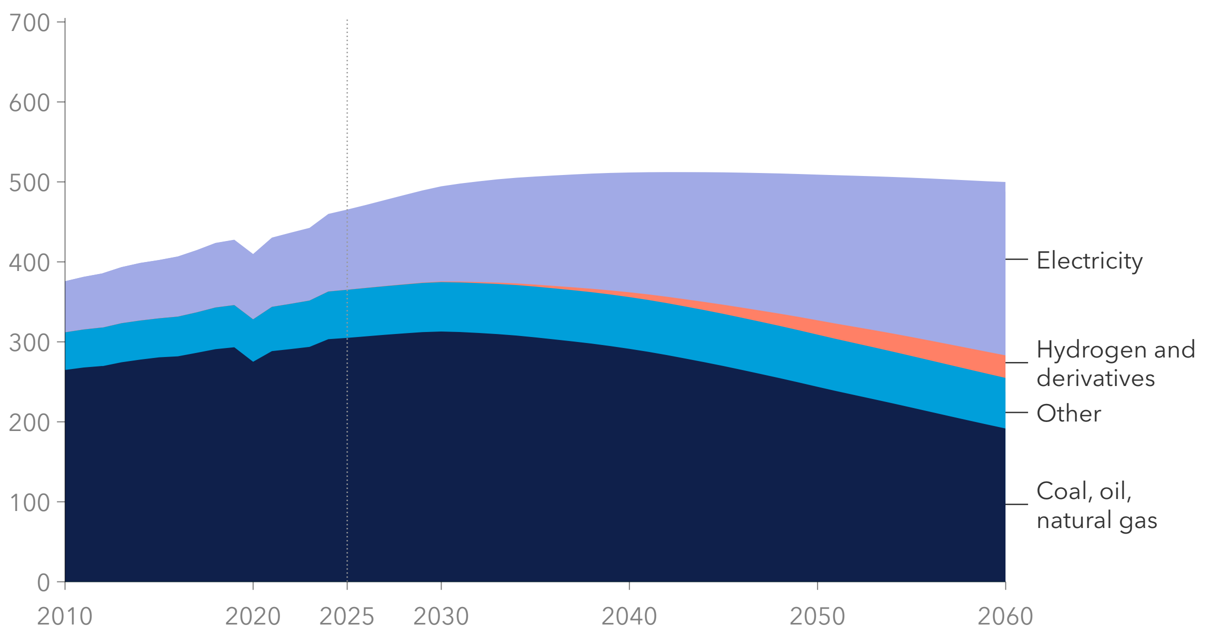
- The actual need for energy, or useful energy, increases in the three main demand sectors: transport, manufacturing, and buildings.
- However, electrification leads to massive efficiency gains, with ever lower losses. This is a key reason for energy demand plateauing in spite of the GDP growth.

Primary energy supply (EJ/yr)



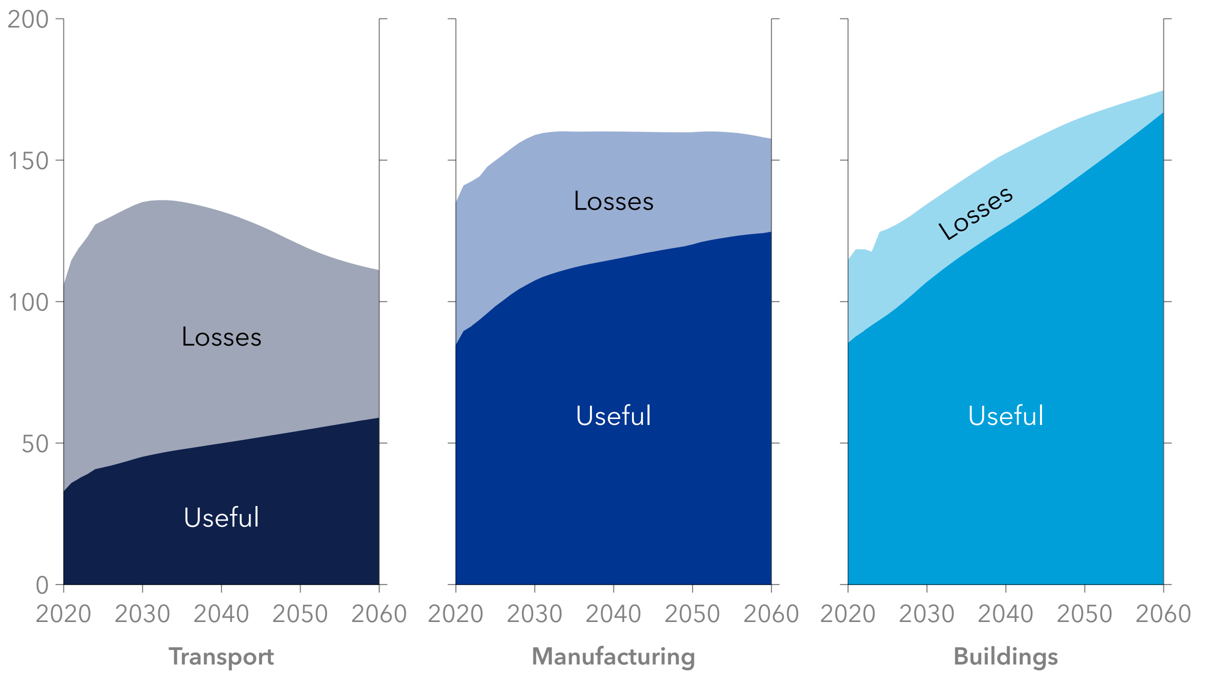
Historical data source: IEA WEB (2025)

Final energy demand by carrier (EJ/yr)



Other includes direct heat, bioenergy, solar thermal, and geothermal. Natural gas includes biomethane. Electricity includes self-generated electricity. Historical data source: IEA WEB (2025)

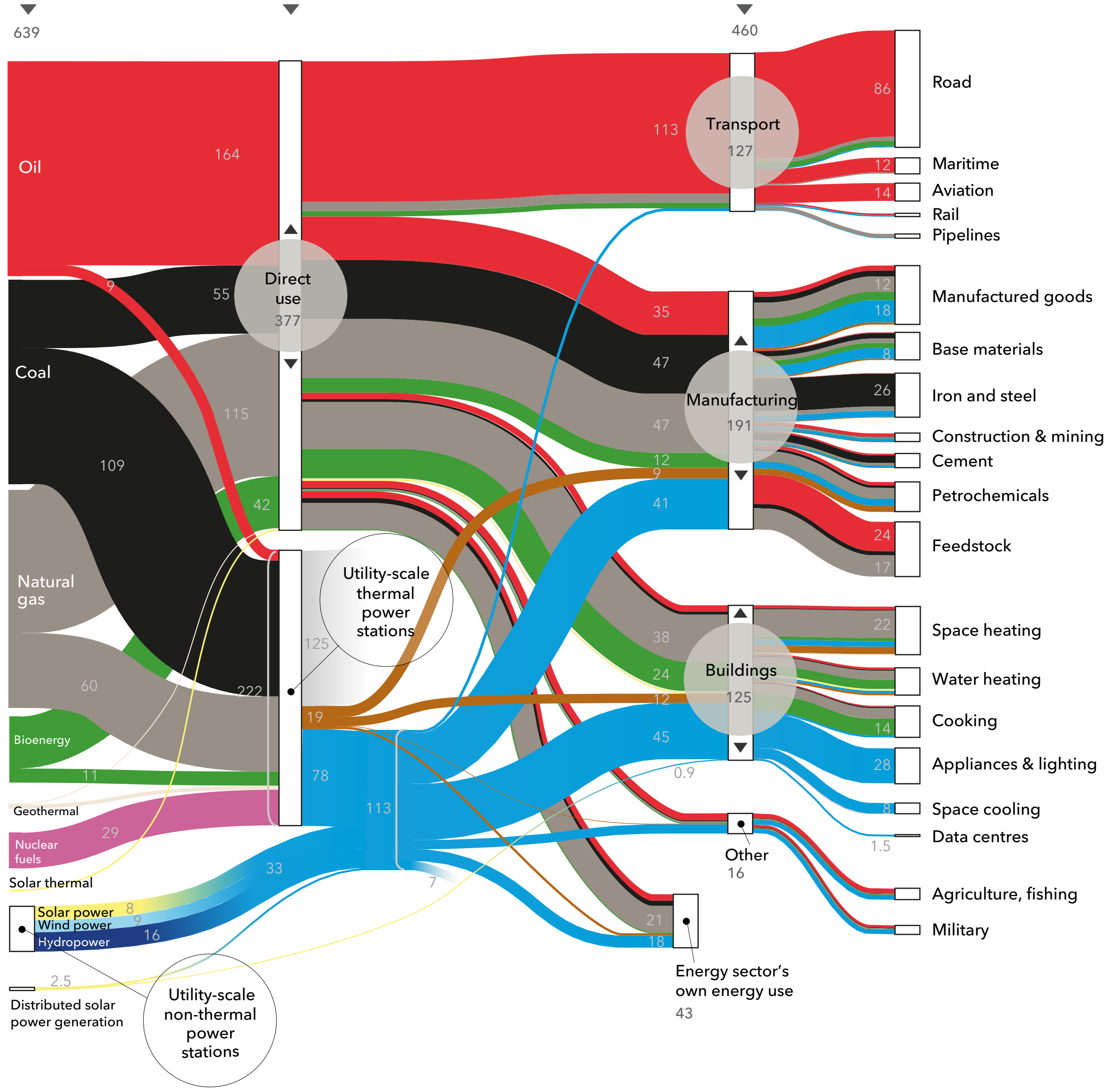
Final energy demand by sector (EJ/yr)



Historical data source: IEA WEB (2025), DNV analysis for useful energy

Comparison of energy flows

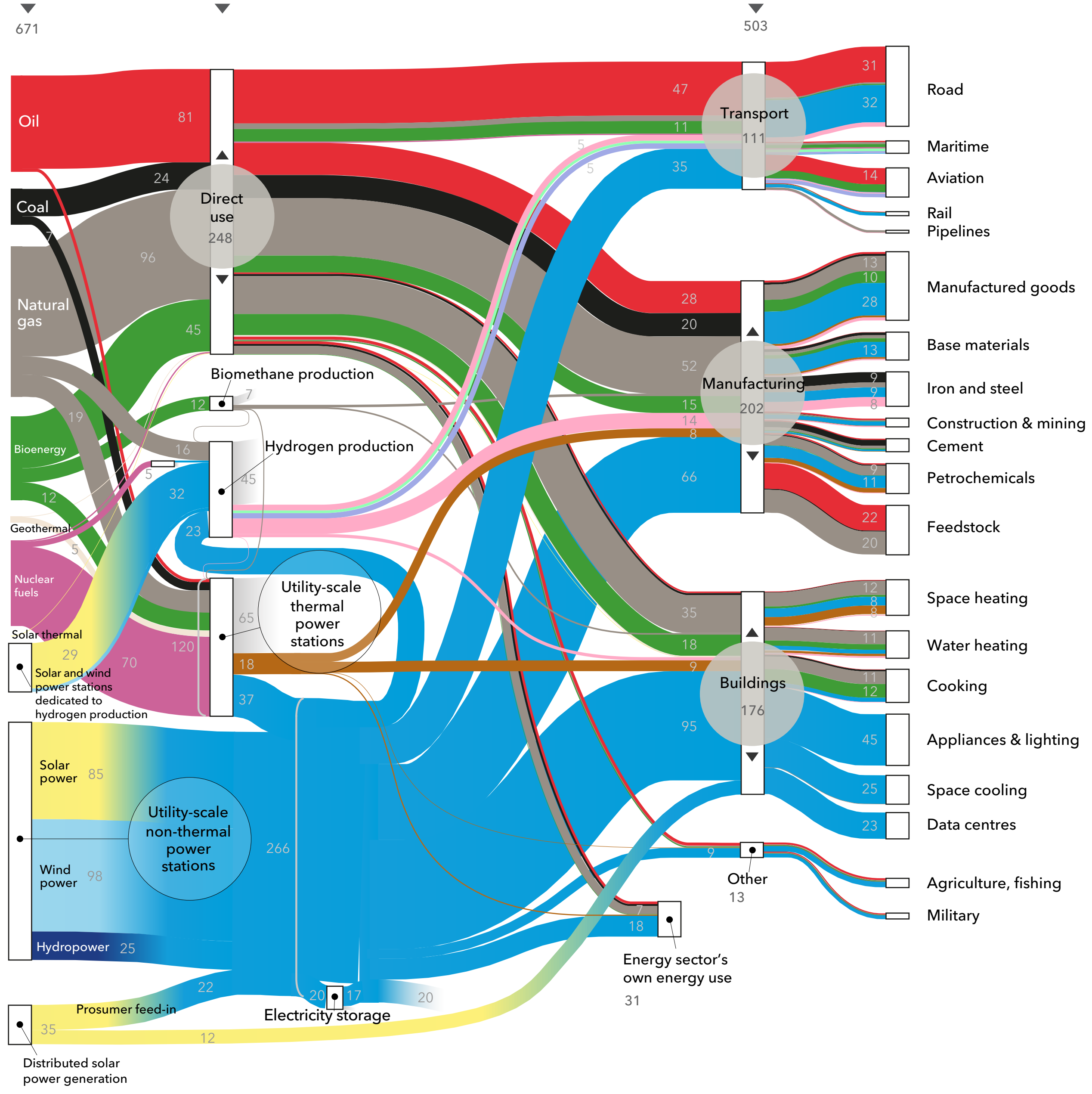
2024



Scale

0 50 100 150 200 EJ/yr

2060



- Oil
- Coal
- Natural gas
- Hydropower
- Wind power
- Solar power
- Bioenergy
- Geothermal
- Nuclear heat
- Electricity
- Heat
- Hydrogen
- Methanol
- Ammonia

2.2 THE COMPETITION BETWEEN FOSSIL AND NON-FOSSIL ENERGY

The most critical aspect of the global energy transition is the replacement of fossil energy by non-fossil energy. That is easier said than done; fossil energy currently represents 80% of all energy use, and has done so for more than 60 years. One could therefore conclude that the global energy transition has not yet started.

However, we believe that the transition has started, but the change is gradual and almost imperceptible at a global level. Global energy-related emissions are most likely peaking in 2025 and will start to fall from 2026 onwards. In other words: henceforth we have a 'live' global energy transition. The 80/20 split in favour of fossil sources is a global average. In some regions, the mix already leans more in the direction of non-fossil energy. Europe is the best example, but even there the fossil fuel share has only reduced from 90% in 1980 to 69% today.

Non-fossil grows fast and overtakes fossil in the 2050s
Primary energy demand (EJ/yr)

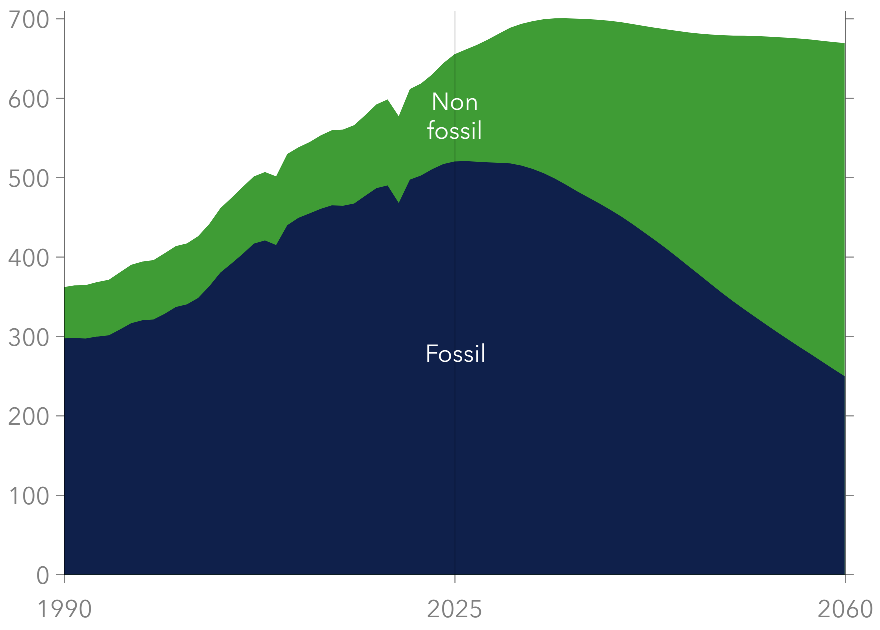


FIGURE 2.1 | Historical data source: IEA WEB (2025)

From energy addition to energy transition
Primary energy demand (indexed to 1990)

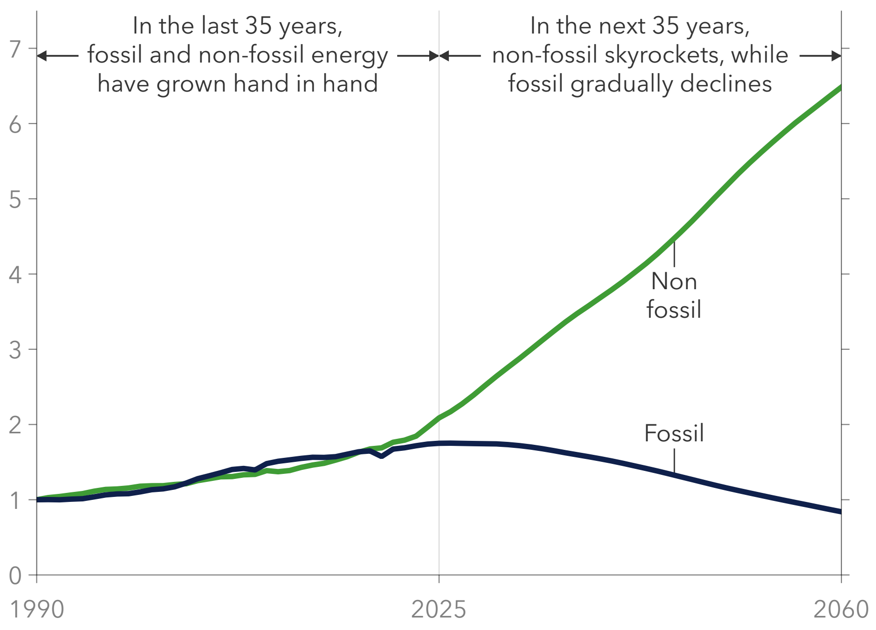


FIGURE 2.2 | Historical data source: IEA WEB (2025)

We forecast that the fossil fuel share of primary energy will reduce by more than 1% per year, from 80% today to 36% in 2060. By historical standards, that pace of change is unprecedented. However, the transition is not fast enough to reach *Paris Agreement* climate targets. The transition is likely to leave most stakeholders dissatisfied: far too slow to prevent dangerous climate change as the IPCC defines it and fast enough to disrupt the vast fossil fuel industry and bring turmoil to fossil fuel exporting countries that have enjoyed decades of profit and power.

However slow it may be, the transition is inevitable. No policy reversals, budgetary deficits, or geopolitical crisis will stop it. Solar PV, onshore wind, and batteries – the three most important technologies needed for the transition – are now so inexpensive that they outcompete fossil energy in a constantly growing number of areas. While the direction of the transition is set, the pace of the transition is not a given. The DNV ETO Model incorporates all the principal forces pushing and opposing the transition.

Fossil energy has many advantages:

- Abundance in many locations makes production inexpensive.
- High energy density makes its use comparatively easy and inexpensive.
- High energy density makes it easy to transport (particularly oil and coal).
- Well-established infrastructure.

Despite these advantages, fossil power has several disqualifying disadvantages. The main problem is emissions: the global energy system is responsible for 70% of global emissions. Second, from a health perspective, local emissions and particulates released during production, especially combustion, are also a major issue. A further big disadvantage is the ineffectiveness of fossil fuels: most of their energy is lost as heat in the combustion process. This contrasts sharply with renewable generation, which is 100% efficient in the sense that no tradeable energy is lost. Finally, the geographic concentration of fossil fuels makes them good for exporters and bad for importers from an energy security perspective. From a physical security perspective, centralized facilities (e.g. large refineries and depots) and pipelines are more vulnerable than distributed renewables.

Fossil fuels have important uses beyond energy which adds to their staying power. Today, 14% of the world's oil, 10% of the gas, and 1% of the coal is used for feedstock in plastics, petrochemicals, asphalt, and similar products. This fossil fuel is not burned and does not cause direct emissions. As the use of fossil fuel for energy declines towards 2060, the non-energy share will grow (see Section 5.4 for a detailed description of feedstock).

Renewable energy also has many advantages:

- No GHG emissions, except very small amounts for construction.
- Not dependent on any finite source.
- Generally very high efficiency (with a clear exception for traditional biomass which has a high ratio of energy losses during combustion).

– Renewable resources are ubiquitous and therefore energy secure (apart from solar in extreme latitudes).

The main disadvantages of solar and wind are variability and storage difficulties. Additionally, low energy density makes these sources area intensive and leads to high costs in some instances. However, research and pilot projects point to considerable opportunities for co-locating agriculture with solar and wind and aquaculture with offshore wind. CAPEX costs dominate and upfront costs can be a barrier without access to favourable financing.

Transport (as electricity) is challenging and includes losses. In past decades, the low technology maturity for new renewables like wind and solar historically made them expensive. Now that onshore wind and especially solar are very cheap, their proliferation is inevitable.

Nuclear energy is not, by definition, renewable because it relies on finite fuel sources, but we include it in non-fossil fuels because it is a carbon-free energy source. Most other non-fossil sources are renewable and their share of the energy mix will grow much more than nuclear over the next three to four decades.

World primary energy by source (EJ/yr)

Source	2024	2030	2040	2050	2060
Wind	9	15	31	62	99
Solar	13	32	68	107	148
Hydropower	16	19	22	23	24
Bioenergy	57	62	69	77	69
Geothermal	4	6	7	7	5
Nuclear	29	37	48	59	75
Natural gas	169	183	190	164	131
Oil	177	179	154	118	86
Coal	171	157	106	62	32
Sum fossil fuel	517	518	451	344	250
Sum non-fossil fuel	127	171	245	335	420
Total	**645**	**689**	**696**	**679**	**670**

TABLE 2.1

2.3 ENERGY EFFICIENCY

Between now and 2060, the global economy nearly doubles in size, but primary energy supply hardly grows at all. This outcome depends on a single structural change: using energy more efficiently at every stage. Smarter system design, better equipment, and behavioural shifts collectively offset over 40% of the demand that rising activity would otherwise generate. Energy and GDP are decoupling in the coming decades – not because less is done, but because less energy is needed to do it.

Figure 2.3 shows the chain from primary energy to useful energy.

– **Primary energy** includes fuels like coal and gas and electricity from wind and solar. Much of the primary energy is lost as heat to produce final energy.

– **Final energy** is what reaches a user's residence or assets like a car (e.g. electricity, petrol, gas).

– **Useful energy** is what remains after conversion losses during end use (e.g. heat losses in an internal combustion engine) and powers services: motion, heat, or light.

Activity pushes demand up, but avoided demand – lower upstream losses and higher end use device efficiency – pulls it back down. These shifts come not from one breakthrough, but from thousands of small choices: to travel differently, insulate better, replace a boiler, or recycle.

At present, just under half of all global primary energy becomes useful energy. The rest is lost – roughly 28% upstream, another 29% in end-use equipment.
Losses vary:
– coal plants operate below 40% efficiency
– oil refining consumes 7% of its input to produce oil products
– most car engines lose 70% of fuel energy
– building heating often wastes more than a third of its input

These losses are not just physical, they're economic. Consumers pay for energy they never use and importing countries bear the full cost of wasted fuel, compounding exposure to price and supply shocks.

Even small efficiency gains add up. A 1% improvement in global conversion efficiency can save more energy than an entire mid-sized country consumes. The story of how energy demand stays flat while the world economy grows lies in how these losses are being avoided: through changes in behaviour, technology, and the structure of the energy system itself.

Useful energy grows, but slower than the economy
If past trends held, useful energy demand would rise with GDP – about 96% over the next 36 years. Instead, our assessment shows a slower increase. Useful energy grows by only 45%, implying a 50% saving relative to the historic trajectory. This difference comes from shifting demand patterns and the growing impact of behavioural and structural change.

These changes often go unrecorded. Statistics do not track kilometres walked instead of driven or rooms that no longer need heating due to better insulation and ventilation. But the effect is real. When such shifts scale – through regulation, pricing, or social norms – they materially reduce energy demand.

Not all useful energy is immediately apparent to the end user as heat, motion, and light. Some services – computation, communication, digital media – deliver value in ways that are harder to quantify in terms of an individual's energy footprint.

Data centres in particular illustrate this point: they are shared by billions of users, whose energy use is almost impossible to track through the large quantities of electricity at server farms. Between 2010 and 2020, workloads – the volume of data processed and computations performed – rose by more than 550%, while energy use increased by just 5 to 15% (IEA, 2025). That gap reflects advances in chip design, memory integration, server utilization, and cooling – plus the shift from underused enterprise hardware to cloud-scale infrastructure. Global power usage effectiveness (PUE) – the ratio of total energy use to energy reaching servers, with the rest consumed by cooling and other auxiliary systems – fell from around 2.0 in 2010 to 1.4 by 2024 (IEA, 2025).

AI brings a different challenge: dense, high-throughput computation that pushes up energy intensity. But here too, gains are emerging through algorithmic optimization, custom processors, and innovation in cooling systems. What matters is not each improvement on its own, but how they interact. When software, hardware, and operations all advance together to create multiplying efficiencies, energy per unit of computation keeps falling even as demand keeps rising (Lovins, 2025).

Energy demand also falls when systemic design and infrastructure shape behaviour. Fewer car journeys are needed when cities are built for access rather than speed. Smaller dwellings, used more intensively, require less energy per person. Shorter supply chains and greater materials circularity reduce industrial energy inputs and embedded emissions.

Not all behavioural change is durable. Lower energy bills can lead to rebound effects, where improved efficiency is partly offset by increased use or consumption elsewhere. Efficiency gains may encourage larger vehicles, higher indoor temperatures, or longer travel distances. However, these effects remain limited in our modelling. The long-term trend is one where energy services continue to grow, but at lower energy cost per unit delivered.

Growth in global energy demand to 2060 is shaped more by efficiency and structural change than economic expansion
Global energy demand (EJ/yr)

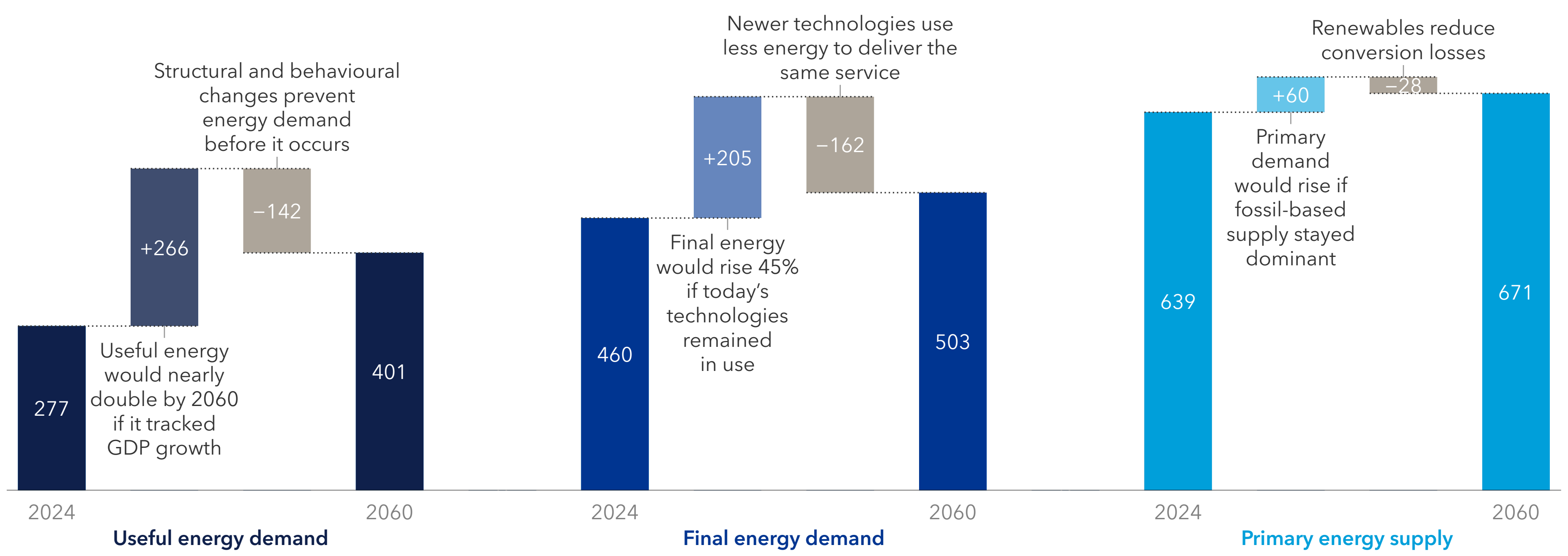


FIGURE 2.3 | Historical data source: IEA WEB (2025) for primary and final energy, DNV estimates for useful energy

Technology shift reshapes final energy use
The most significant absolute savings in final energy come from more efficient equipment and better system design. These are not minor upgrades. In many sectors, they mark a fundamental shift in how energy is used. In most cases, efficient electricity is the key enabler.

EVs convert over 90% of electricity into motion – three to four times better than combustion engines. As they scale, transport energy demand drops even if distance travelled rises. Heat pumps offer a similar step change, delivering two to four units of heat per unit of electricity. Replacing gas boilers with heat pumps cuts energy demand sharply in buildings and low-temperature industrial applications.

Large losses occur after energy reaches end users inside vehicles, boilers, motors, and other equipment (Figure 2.4). Combustion engines, traditional furnaces, and resistive heating account for much of the gap between final and useful energy. Shifting from combustion to efficient electric technologies delivers the largest absolute savings.

Incremental gains also matter. LEDs, motors, and smart controls reduce losses. Industrial optimization and waste heat recovery improve overall performance. Once high-efficiency stock dominates, progress slows; motors already exceed 90% efficiency and heat pumps operate near thermodynamic limits. Further gains depend on integration, not component design.

Transformation losses fall as renewables rise

The shift to renewables changes how energy is counted – and how much is lost. In fossil electricity generation, over half the input energy is lost as heat. Even the best gas combined-cycle plants operate below 65%, and global averages are lower. Nuclear is also treated as a thermal power plant, with primary energy based on reactor heat rather than electricity output, with an assumed efficiency of 33%. The overall efficiency of thermal power plants has improved only marginally from 36% in 1980 to about 40% today.

In contrast, solar and wind are counted as primary energy at the point of generation. There is no fuel and no combustion, so no thermal loss. As these sources grow, power system efficiency rises because fossil-era conversion losses are avoided. By 2040, wind and solar deliver more electricity than all other sources combined. As a result, average global power system efficiency increases from 48% today to 62% in 2040 and 78% by 2060.

Hydrogen and its derivatives introduce new losses between final and primary energy, whether produced via methane reforming or electrolysis. The global efficiency of hydrogen production remains below 40%.

End-use energy losses are reduced as we transition to electric motors and heat pumps

Global final-to-useful energy conversions in 2024 and 2060 (EJ/yr)

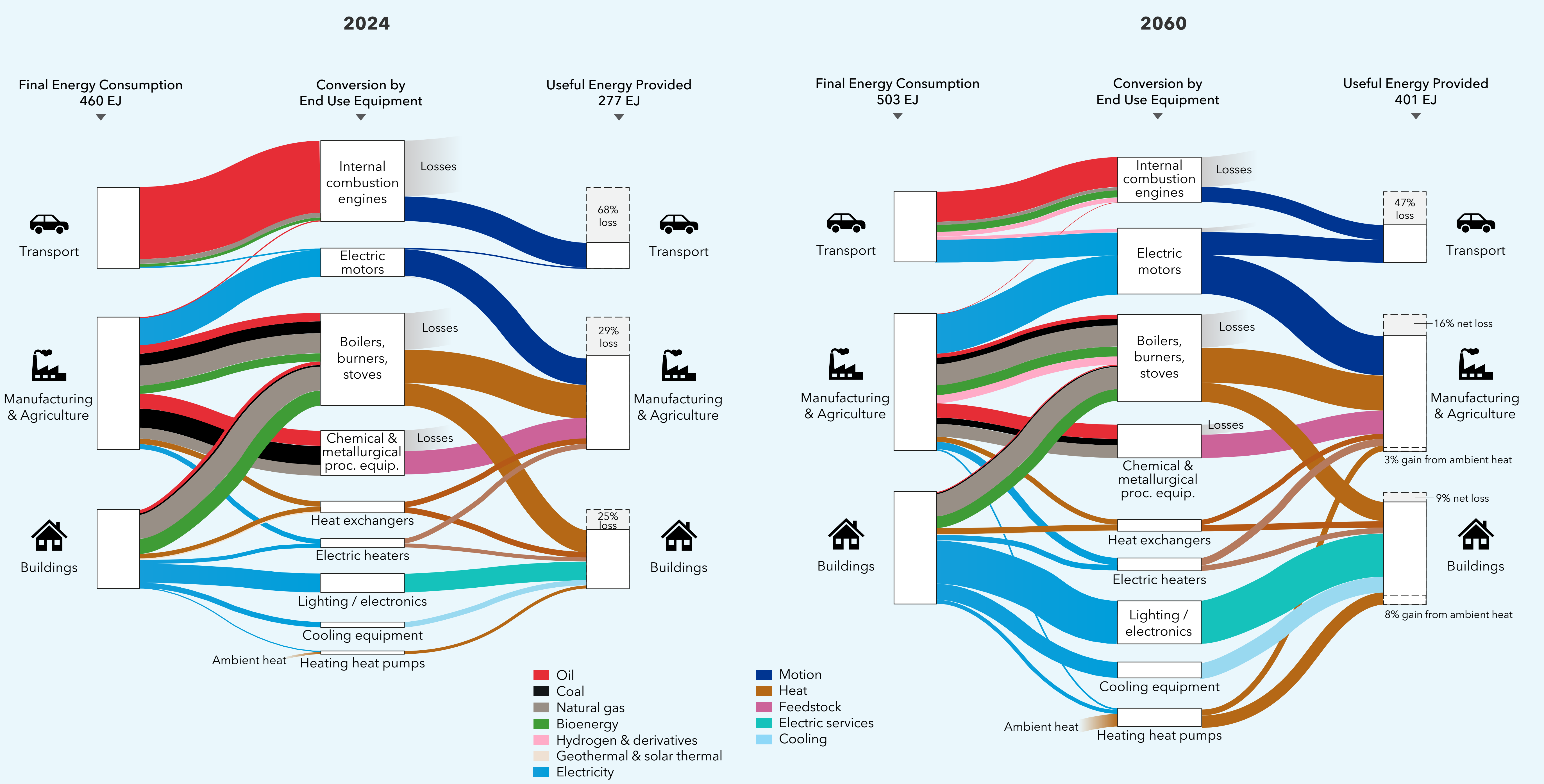


Figure 2.4 | Historical data source: IEA WEB (2025) for final energy, DNV estimates for useful energy. Lighting and appliance use are shown without losses, as they provide services like illumination or functionality; for cooling, electricity input is treated directly as useful energy, since removed heat is not delivered but rejected to the environment.

2.4 AI AS A MAJOR SOURCE OF ENERGY DEMAND

Today's expansion of artificial intelligence is profoundly physical. It is dependent on a capital-intensive data centre buildout and the electricity to run it. For those forecasting the energy system, the central concerns are the progress and speed of AI demand and the requirements of the supporting electricity system. This section sets out the framework we use to estimate demand for AI services. In Chapter 3 (page 25) we translate this demand into the energy footprint of AI and other data centres.

Adoption of AI at scale is impeded by hardware and supply-chain limitations, deficiencies in data availability and quality, energy and grid constraints, regulatory restraints, and the need for robust assurance of safety when deploying AI in critical systems. We therefore expect that AI adoption will not be gravity defying. The steady embedding of AI will produce material aggregate productivity effects in the pattern of historical, technology-based improvements in labour productivity rather than unlock unquantifiable value creation through a rapid transition to super-intelligence (Kokotajlo et al., 2025).

Unprecedented buildout

AI systems have advanced in perception, language, and decision support, partially replacing tasks that previously required human cognition. Some studies have reported productivity gains. For instance, a large-scale field study in customer support found 14 to 15% higher agent productivity, with the largest effects for novices. Another experiment on mid-skill professional writing found substantial time savings with quality improvements (Brunjolfsson, 2025; Noy, 2023). Although still facing important conceptual and physical constraints, embodied AI has started to extend automation into the physical environment (e.g. warehousing, constrained manufacturing tasks), supporting the claim that AI may eventually replace or augment an expanding share of both cognitive and manual work. The macroeconomic potential follows from the scale of human labour in value creation, where labour compensation accounts for roughly half of GDP across many economies (Our World in Data, 2025), so even partial automation can carry large aggregate value if it can be deployed reliably and safely.

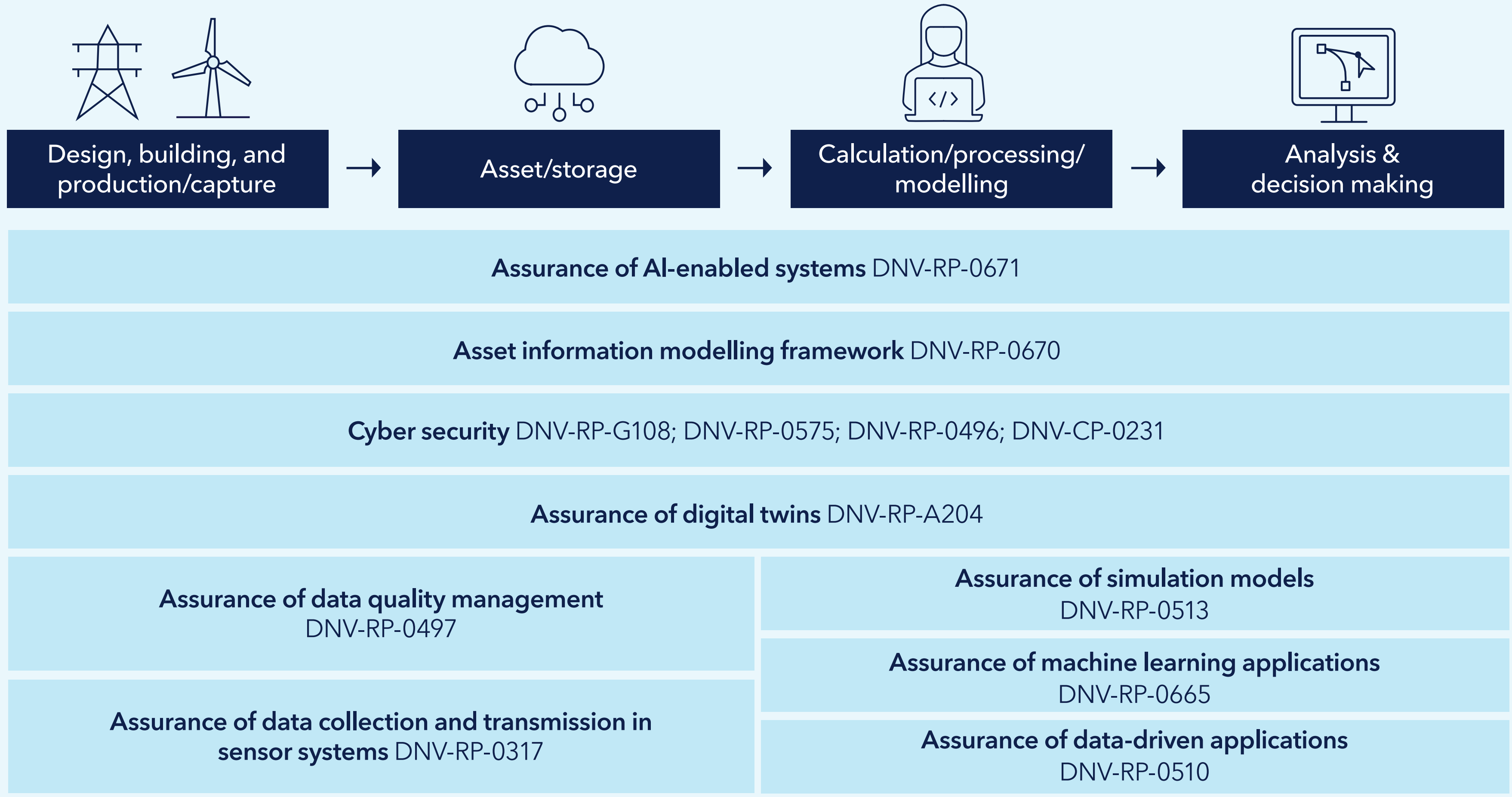
Over the past two years, hyperscalers have embarked on an unprecedented build-out of AI infrastructure, with estimates of over USD 500bn in AI-related capital expenditure (data centres, accelerators, networking) and year-on-year growth close to 50%. The spending spree has led to intensified investor scrutiny since the reported AI revenues have not, thus far, matched the pace of capital outlays (Morris, 2025). Despite these concerns, we can

Industrial deployment of AI

Embedding AI into industrial applications that need a high level of safety elevates assurance from a desirable property to a prerequisite condition for deployment. Assurance of AI-enabled systems involves a comprehensive assurance process for all the building blocks in the advanced digital systems applied to critical infrastructure (see graphic below). Emerging assurance frameworks supply governance structures and timelines. The *ISO/IEC 42001 (AI management systems)*, the NIST *AI Risk Management Framework* (AI RMF 1.0), and EU *AI Act* all focus on managing AI risks. Together, these will shape market access and procurement norms for 'Industrial AI' in the energy sector, e.g. power systems, manufacturing, and mobility (DNV, 2024a; NIST, 2023; EU, 2024).

DNV's complete set of recommended practices for digital applications

THE BUILDING BLOCKS OF ADVANCED DIGITAL SYSTEMS



already see some measurable gains from current AI deployment. The narrow (but real) improvements and the 'winner takes all' promise of successful General AI deployment explain both the continued capital formation and the investor focus on when, not if, returns start to scale beyond pilots.

Cautious adoption

The lukewarm reception to new models in the summer of 2025 highlighted the growing perception that year-on-year advances in frontier models (highly capable general-purpose models) are incremental rather than transformative (Newport, 2025). Inside companies, adoption remains limited and lags the prevailing narrative. In the EU, only 13.5% of enterprises reported any AI use in 2024 (41% among large firms), underscoring a wide diffusion gap (Eurostat, 2025). The US Census Bureau's *Business Trends and Outlook Survey* shows AI use rising from 3.7% (Sep 2023) to 5.4% (Feb 2024), with about 6.6% expected by early autumn 2024. This is early confirmation that diffusion is real but still in its infancy (Bonney et al., 2025).

The productivity paradox–again

The 'productivity paradox' associated with prior general-purpose technologies helps interpret the AI adoption pattern. Such technologies require complementary, often intangible, investments (data quality, workflow redesign, integration, skills, and assurance) that depress measured productivity before later gains materialize (Duperrin, 2025, Brunjolfsson, 2021). Consistent with this, recent OECD analysis anticipates meaningful but gradual macro-productivity effects from AI under realistic adoption scenarios, rather than immediate step-changes (OECD, 2025). These observations support a near-term outlook of domain-specific deployments with measurable gains where data are reliable, tasks are repeatable, and assurance is feasible.

> We expect global data-centre electricity demand to more than double by 2030, with AI a central driver.

Energy use

Training and inference economics sit at the intersection of hardware efficiency, model design, and system optimization. Recent empirical work indicates leading ML hardware energy efficiency has been improving by roughly 40% per year (about double every two years), even as overall compute demand surges (epoch.ai, 2025). At system scale, energy use is driven by countervailing forces. Rising demand for digital/AI services vs improvements in energy per computation. We forecast global data-centre electricity consumption to more than double by 2030, with AI-optimized centres a central driver linked to siting, cooling, and grid-connection constraints (see section 3.4 for details). In our forecast, historical efficiency gains continue alongside rising aggregate demand, with net outcomes shaped by architectural choices (frontier-scale vs smaller, domain-specific models), hardware improvements, and the balance between centralized cloud inference and edge deployment.

How big will AI get?

We forecast that AI will be increasingly embedded across the economy by 2030. However, the present rate of investment in AI will probably cool as it becomes apparent that aggregate gains from real-world AI deployment will likely align mainstream productivity ranges rather than a step-change. This view is consistent with OECD micro-to-macro modelling of AI's contribution to labour-productivity growth across G7 economies under realistic adoption paths (OECD, 2025). Our ETO forecast assumes continued efficiency improvements and maturing assurance ecosystems, tempered by compute, energy, and integration bottlenecks that slow uptake of AI outside of those sectors to which it is well suited. These sectors are information-rich, workflow-standardized, and KPI-visible – a sweet spot where AI can see, read, predict, and decide with humans in the loop, to produce fast, auditable ROI (e.g. customer support, finance, legal, marketing, and computer programming).

The public debate on how quickly uptake of AI will happen remains polarized. Some analysts argue that progress in LLMs has stalled and that current enthusiasm resembles a bubble, while others forecast extraordinarily rapid take-off scenarios (such as 'AI 2027') with superintelligence in a few years.

Given assumptions about compute capacity improvements, semiconductor throughput, model efficiency, and energy-infrastructure build-out, we forecast substantial technical progress and continued market growth. However, the expansion in the amount of cognitive work performed or supported by AI remains more modest than scenarios positing AI as a replacement and not merely a 'helper' technology for performing deep cognitive tasks. High-risk industrial applications, such as grid balancing, autonomous driving, and complex automated manufacturing, carry material safety, reliability, and liability risks. Because those risks need to be addressed through rigorous assurance, certification, and operational controls, the rollout of industrial AI is likely to proceed at a pace determined by regulatory approvals, demonstrable risk reduction, and stakeholder acceptance, rather than vendor roadmaps.

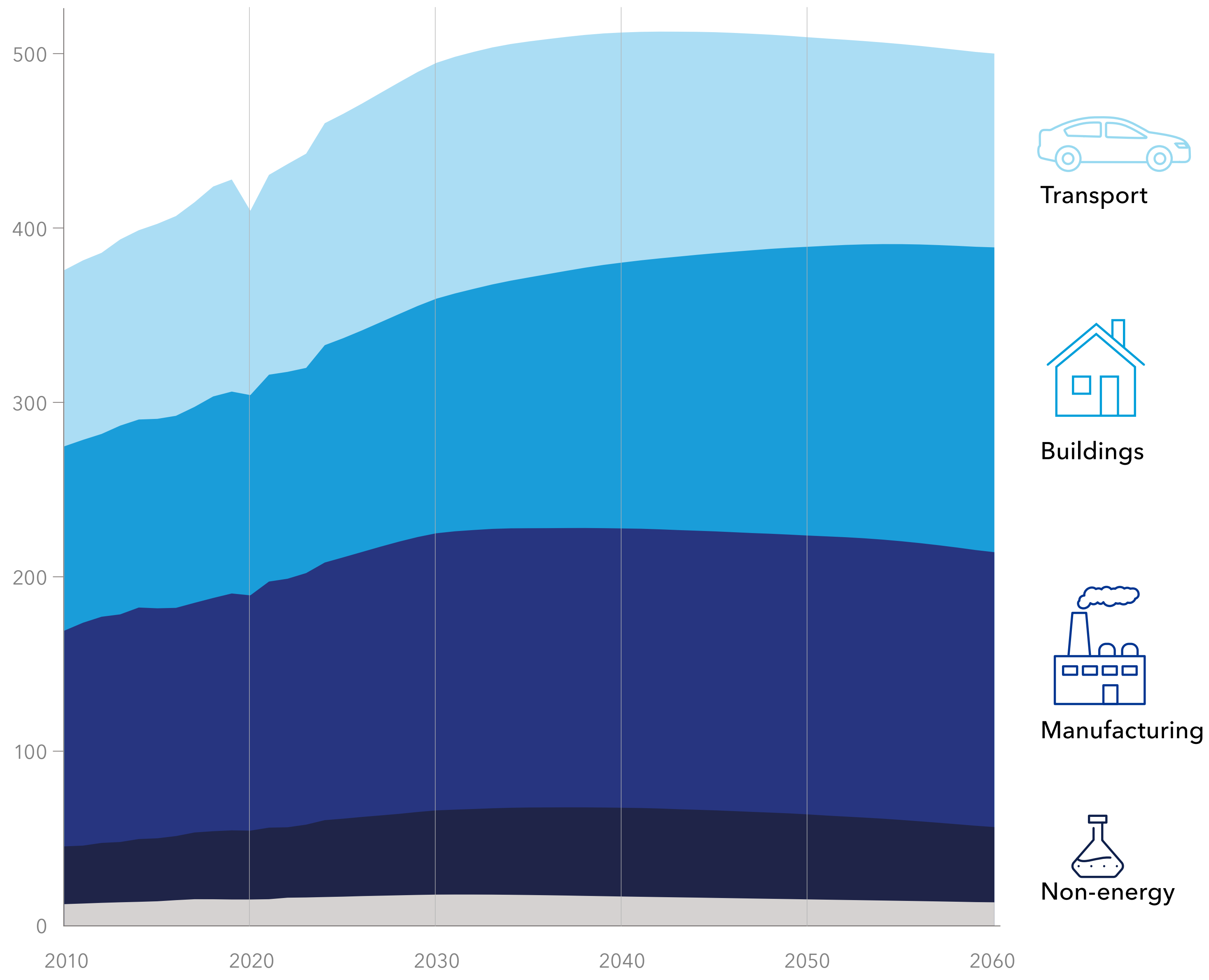

Supercomputer data centre in the Netherlands

2.5 DEMAND SECTORS

Three different trajectories for the three main demand sectors

Final energy demand by sector

(EJ/yr)



Historical data source: IEA WEB (2025). Bottom category: Other sectors

TRANSPORT

Demand for transportation services will grow. However, EV uptake in road transport, the most energy-demanding sector, means that **energy demand levels off and then falls** from the mid 2030s. The hard-to-electrify aviation and maritime will also move away from oil dominance to a more diversified and decarbonized fuel mix.

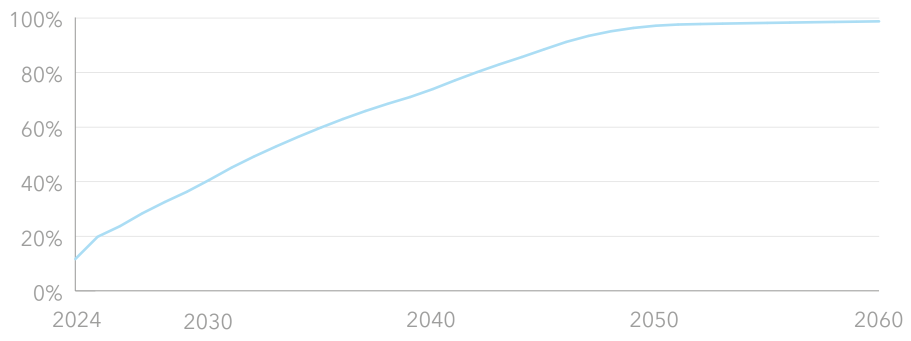
BUILDINGS

Energy demand will **continue to grow**, driven by a more affluent population using more appliances and an increased demand for space cooling. The only end-use that will decline is space heating, as efficient electrical heat pumps progressively replace traditional gas boilers.

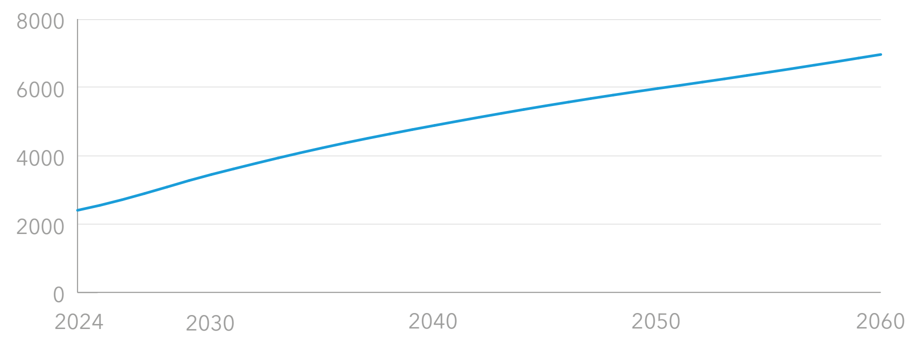
MANUFACTURING

Energy demand will see **little transformation** compared with other sectors. Due to cost-driven global competition, heavy industries will rely on fossil fuels for high-temperature processes for the next few decades. Meanwhile, the faster pace of cost-competitive electrification of goods manufacturing will create global competition for the future location of high-tech industries.

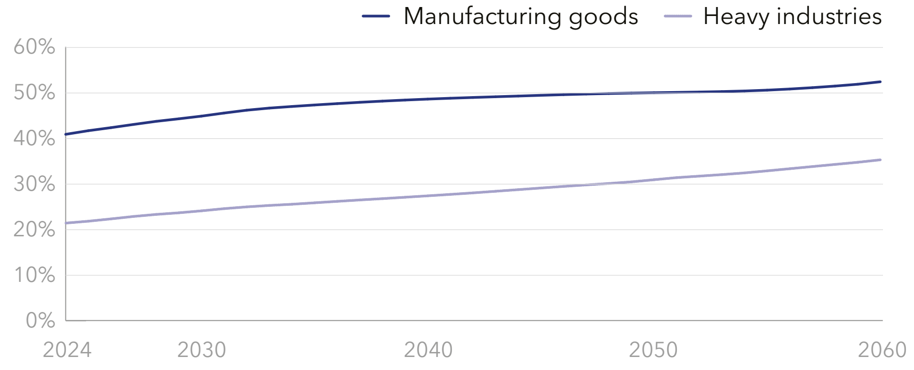
Global share of EVs in new passenger vehicle sales



Global space cooling demand (TWh/yr)



Share of electricity in energy demand



NON-ENERGY, the use of energy carriers (mostly fossil fuels) as chemical feedstock for plastics, chemicals, asphalt, etc., will continue to grow in the next decade before higher plastics recycling rates curb the demand of virgin material made from oil and gas.

2.6 TRANSPORT

Growing transport demand

- The demand for transport by road, rail, and aviation will grow 2-3% per year, relative to 2024 levels. This growth is correlated to the growth in population and GDP.
- The demand for maritime shipping will plateau in the 2030s and become decoupled from GDP growth. Key reasons are declining fossil fuel shipments (due to the energy transition) and a shift towards a more service based global economy.
- Despite growing transport demand, its final energy demand will peak at 140 EJ/yr in the early 2030s, mainly owing to efficiency gains from road transport transitioning to EVs.
- Transport patterns will change: Some short-haul flights will be replaced by high-speed train; urban transport will switch to public transport; shared autonomous vehicles will displace a portion of privately-owned passenger vehicles.

2029

Year of peak oil transport demand at 53 million barrels per day

Declining oil demand

- Oil demand for transport peaks at 53 Mbpd in 2029. From 2030, the demand will drop an average of 1 Mbpd annually.
- All transport sectors will decarbonize, albeit at different rates: e.g. the oil demand from aviation does not decline, despite decarbonization, due to increasing travel demand.
- In 2032, global EV share will surpass 50% in passenger road vehicle sales. The EV fleet will add an additional 270 TWh of annual demand for electricity each year between 2030 and 2060.
- Maritime and aviation are hard to electrify and must turn to low-GHG fuels. The aviation sector will transition more slowly, while maritime is expected to reduce the fossil share in its fuel mix by more than 3% per year in the 2030s and 2040s. This is driven by a world-wide binding carbon pricing agreement introduced in 2025 by the IMO.

1 million barrels per day

Annual falling oil demand from 2030 to 2060

Transition challenges

- The road sector will benefit from battery technologies continually improving cost and convenience. Optimized, strategic route charger placement is key to rapid EV uptake.
- Biofuel is the next option, in terms of cost, when electrification is impractical. However, the sustainable yield of biomass is limited to about 30% of the fuel demand across sectors.
- The synthetic low-GHG fuels needed in aviation and maritime face the same challenges: they are currently several times more expensive than the fossil option and require abundant cheap, green power. Additionally, they may require new engines, fuel tanks, and port infrastructure.
- Currently, none of the synthetic fuels have a significant market share and there is limited production of the fuels for other uses. This increases the risk of being a first mover and adds inertia to the transition.

270 TWh

Extra electricity needed by EVs per year from 2030 to 2060

Shifting away from oil drastically reduces emissions

Sectoral direct CO_2 emissions relative to an oil-only fuel mix

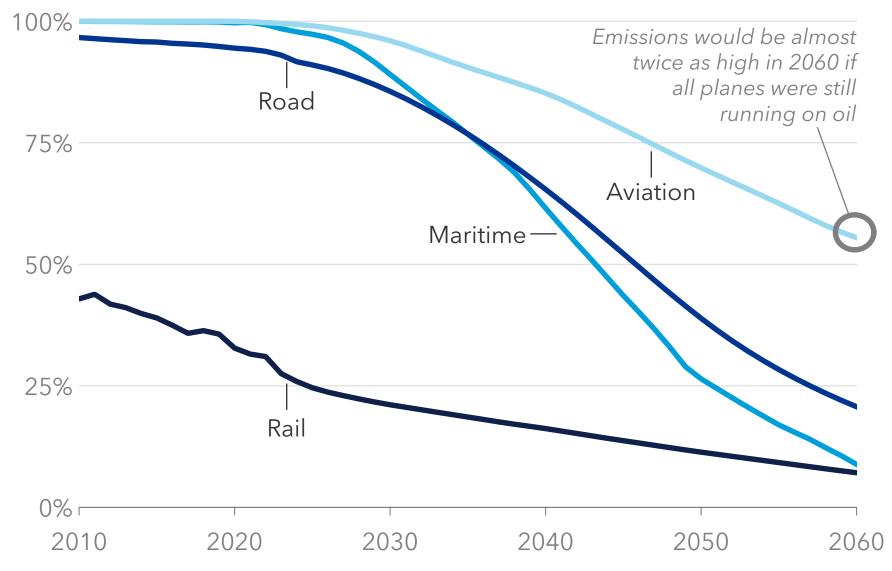


FIGURE 2.5 | Historical data source: IEA WEB (2025)

Energy demand decouples from growth in demand

Transport demand and energy (indexed to 2024)

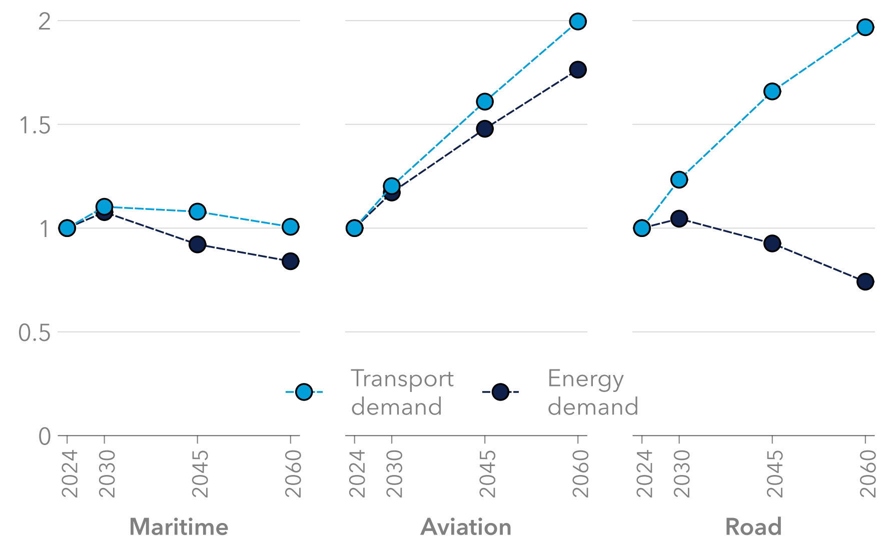


FIGURE 2.6 | Transport demand corresponds to actual transportation demand (e.g. in kilometres or tonne-miles)

Road

Today, road transport comprises nearly 74% of total transport sector energy demand, or 94 EJ/yr. However, by 2060, demand will reduce to 62% of overall transport energy at 70 EJ/yr. This is despite the global vehicle fleet growing from 2.5 billion to 3.8 billion and kilometres travelled doubling from 34 trillion to 67 trillion vehicle-km from now to 2060. Electrification is the driver that will enable these significant sectoral efficiency gains.

The powertrain of EVs can be up to 90% efficient, compared with around 27% for most combustion engines. This means an EV can go three to four times farther with equivalent energy. Considering the energy loss from power plants, EVs charged in grid mixes with varying proportions of renewables can have well-to-wheel efficiencies between 40% and 70% (Albatayneh et al., 2020).

Peak oil demand is approaching for road transport

We forecast that oil use in road transport will peak in the early 2030s (Figure 2.7). This shift is driven by consumers – largely in OECD countries and China – favouring battery EVs as they increasingly perceive both convenience and cost of ownership surpassing conventional cars.

Oil is currently the dominant energy source for road transport, but will cover only a third of total passenger vehicle demand by 2060, with electricity making up the remainder. In middle-income regions such as Latin America and South East Asia, we expect biofuels to play a moderate role in displacing oil, comprising 5% of road energy demand in the region. We do not expect hydrogen, either in fuel cell (FCEV) or direct combustion form, to play a substantial role in the passenger fleet. Globally, biomass and hydrogen will meet approximately 1% of passenger vehicle energy demand.

Oil peaks in 2030, before electricity takes over by 2060
Road energy demand by carrier (EJ/yr)

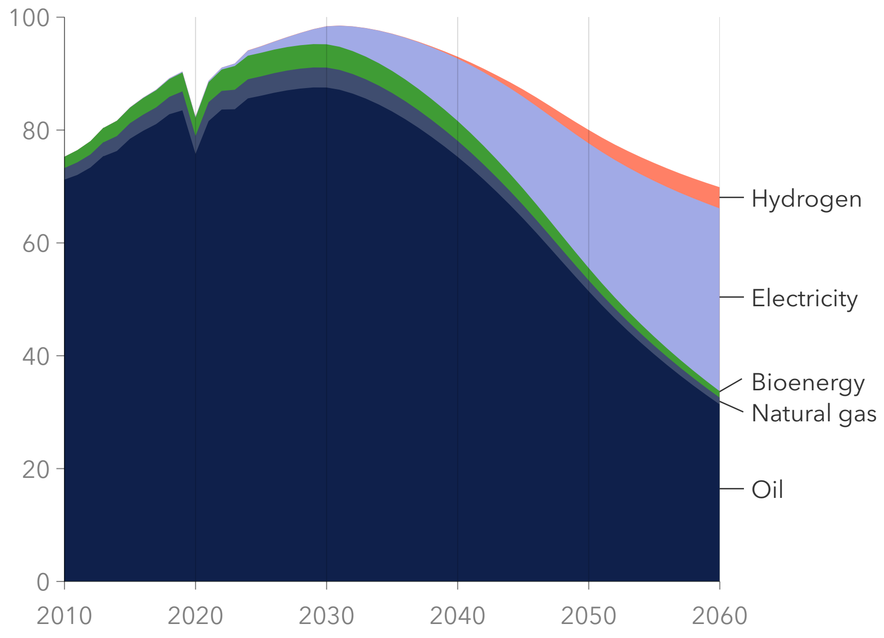


FIGURE 2.7 | Historical data source: IEA WEB (2025)

We also forecast the commercial vehicle fleet will reach peak oil in the 2030s, but the shift lags passenger vehicles due to the technological and logistical challenges discussed below. The global commercial segment will remain dominated by oil through to the end of the 2060s.

One in two passenger cars sold will be electric by the 2030s

We forecast the market share of EVs will grow rapidly in the 2030s, with 2032 being the year where EV sales surpass ICE sales globally (Figure 2.8). This is particularly pertinent given that we expect global demand for passenger vehicle transport to more than double from 22 trillion to 45 trillion vehicle-km by 2060. Greater China and Europe will be the first regions where passenger car sales will be majority EVs, followed by North America. Globally, the passenger car fleet will likely grow from the current 1.4 billion to 1.97 billion vehicles by 2050. After this, we forecast a plateau and slight decline to 1.93 billion passenger vehicles.

We expect automated, optimized ridesharing to reduce the perceived convenience of private vehicle ownership in the coming decades. Moreover, autonomous vehicles have higher utilization rates, providing more passenger travel per vehicle than private cars. These combined effects lead to more passenger vehicles retiring earlier – starting with older, less efficient combustion cars. Without the effects of autonomous vehicles, there would be an additional 15% more vehicles than the ETO forecast and lose out on 6% annual energy savings from combustion car retirements.

The two- and three-wheeler market, especially in Greater China, was already mostly electric in 2024. Combined with emerging markets such as the Indian Subcontinent and South East Asia, we forecast the two- and three-wheeler market will be nearly exclusively electric before 2040.

Policy has been essential in driving EV uptake. A multitude of decarbonization targets have been proposed and legislated across OECD countries and

EVs dominate in car sales by 2030s, and in fleet by 2040s
Global share of EVs and PHEVs in passenger vehicles

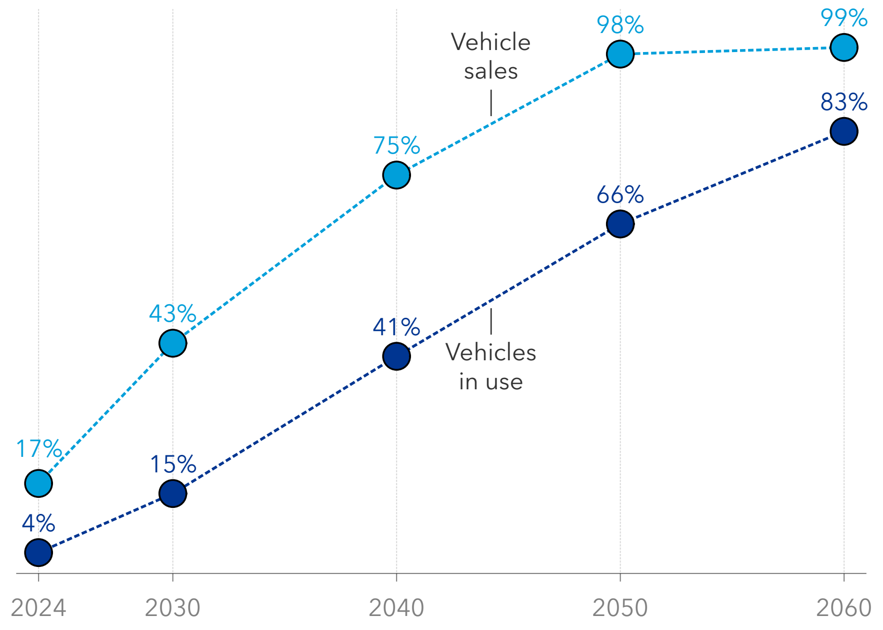


FIGURE 2.8 |

China. Among the more notable is the EU's goal to reduce sales of CO_2-emitting cars and vans by 100% in 2035 – i.e. an ICE vehicle ban (with some exceptions added recently for e- and bio-fuelled engines). We forecast that passenger EVs in Greater China will have an 67% sales market share by 2030. This would surpass their stated target of 60% new energy vehicles (BEVs, PHEVs and FCEVs). India has set an EV sales goal of 30% for passenger vehicles and 80% for two-wheelers by 2030 (Pandey, 2025). While we forecast the subcontinent's passenger EV market share will be 13% by 2030, we expect it to grow quickly to be majority EVs by 2040.

Infrastructure is key – especially for the commercial fleet
For passenger EV fleets, more than 80% of charging is done at home in the evening (Marc, 2023). Charger placement at the workplace is a key optimization strategy to meet daytime charging needs and alleviate peak grid demand (Needell, Wei, and Trancik, 2023).

Commercial vehicles face a combination of technological and logistical barriers to decarbonization. Heavier batteries on long-haul EV trucks could result in reduced payload and revenue per trip and added cost due to charging downtime. Commercial vehicles may also only be able to access to chargers along main corridors, such as the Trans-European Network, where the EU aims to install chargers every 60 km. Greater China has the most chargers at 3 million today and will continue to have the highest installed base at 24.5 million by 2060. The Indian Subcontinent will have 1.4 million fast chargers to meet the forecast demand growth by mid-century.

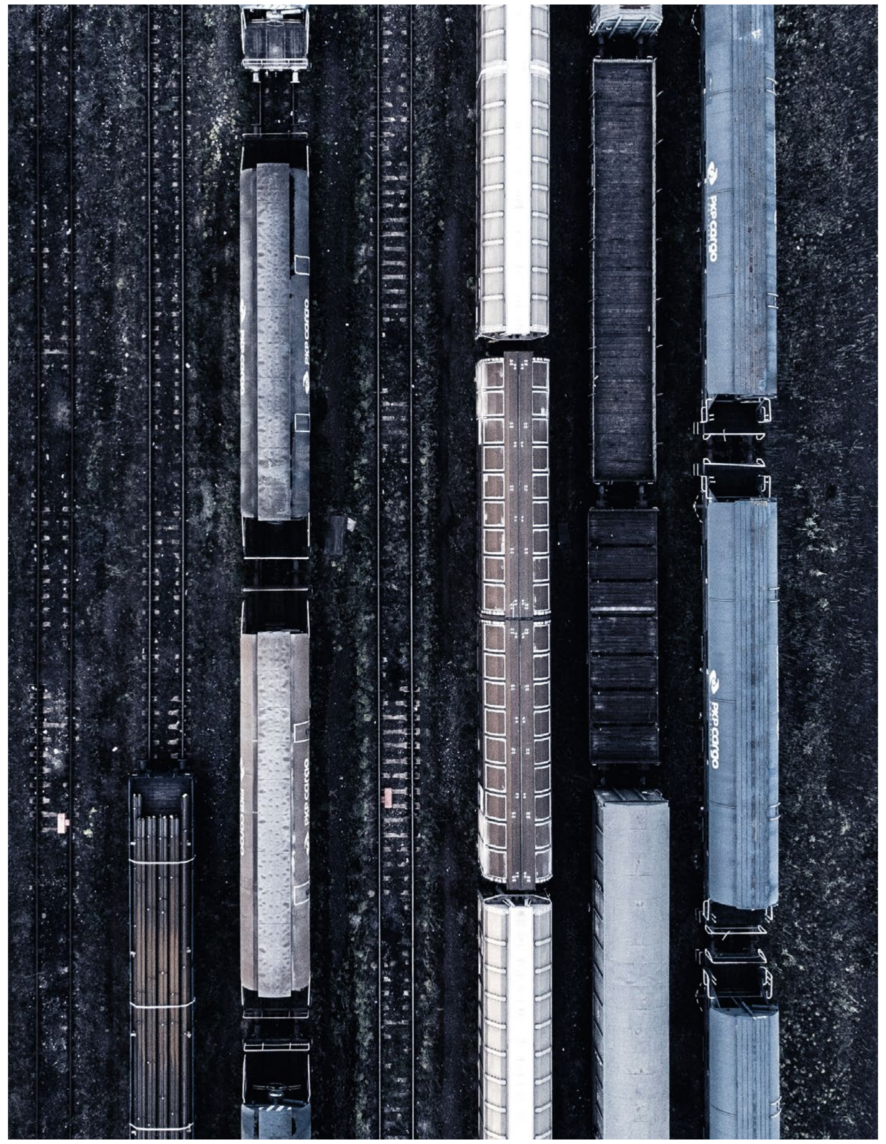
Due to these challenges, we only expect EVs to take a 50% share of new commercial vehicles sales by 2039, except in Greater China, where strong subsidy policies will see this milestone achieved in 2033. We also expect Europe to reach EV-majority market share of commercial vehicles by 2038 through its *Fit for 55* reduction targets.

Globally, the commercial vehicle fleet will continue to increase from 250 million to 440 million units by 2060. However, through decarbonization and EV uptake, we expect energy demand to peak in 2037 at 39 EJ/yr and decline to 35 EJ/yr by 2060.

Charger placement at the workplace is a key optimization strategy to meet daytime charging needs and alleviate peak grid demand.

Rail

The rail subsector consists of all tracked transportation of passengers and goods. It uses only 2% of the energy demand for transport. Today, most freight is transported in Greater China, North America, and North East Eurasia, and most passengers are transported in Greater China, the Indian Subcontinent, and Europe. Going forward, we expect a significant relative growth in Sub-Saharan Africa, South East Asia, and the Indian Subcontinent.



Both freight and passenger demand is growing globally, but not at pace to increase its share of the transport demand. Europe has seen a slowly declining share of freight by rail to 17% over the last decade, well below its target of 30% by 2030 (UIC and UIRR, 2024).

Approximately 50% of the energy demand in rail is already electric – the highest proportion in the transport subsectors – and it will grow steadily to 75% by 2060. However, decarbonization also depends upon renewable power generation to minimize scope 2 emissions.

The main barrier to further decarbonization in rail is the high upfront cost of railways, combined with the long lifetime of existing infrastructure. It is easier to build a new electric railway than it is to electrify an existing one in operation. In addition, some rural railways are too far from the power grid to be electrified. In such cases, biomass, hydrogen, and even e-fuels will take a 9% share in the long term.

Aviation

Demand for aviation transport will grow steadily to double by 2060 from today's level of 4.6 billion person-trips/year. This growth tracks global population and GDP growth – particularly in emerging economies where a larger share of the population will gain access to air travel. More efficient new aircraft and replacing some business travel with remote work will not offset the growth in leisure travel. Unlike the maritime and road sectors where growth is offset by efficiencies, aviation's annual energy use will increase by the equivalent of over 250 million tonnes of jet fuel.

Policy will drive decarbonization, since all alternatives to fossil jet fuel are much more expensive. Currently, sustainable aviation fuel (SAF) deployment targets are predominantly non-binding and only adopted in isolated countries or regions. Among the 10 global regions in the ETO, Europe has the most advanced policy framework, consisting of supply and demand-side policies, carbon pricing, and non-compliance penalties. We forecast the fossil dependence of aviation in Europe to drop to 56% by 2050. This is better than the global average of 70%, but still higher than their goal of 30%.

International agreements, like those in the maritime sector, are needed to speed up the global transition. The ICAO Corsia agreement is a start, aiming to offset emissions beyond 2019 levels for travel between participating states. In the very long term, aviation fossil fuel use does at least level off instead of growing with demand; fossil fuel volumes stay close to 2024's 110 billion gallons. Nevertheless, aviation's share of total energy-related emissions, which is 2-3% today, will grow to 5-6% by midcentury as other sectors reduce their emissions in absolute terms.

	bioSAF	eSAF	Hydrogen	Battery
Feedstock	Biomass	CO_2, H_2*	Green electricity	Green electricity
CO_2, NO_x emissions	Reduced	Reduced	0 (fuel cell)	0
Range	All	All	Short-Medium	Short
Aircraft modification	None (<50% blend)	None (<50% blend)	New	New

*The CO_2 and H_2 required to make eSAF are also dependent on large amounts of renewable or low-carbon electricity.

TABLE 2.2

The low- or zero-emission alternatives are SAF, hydrogen, and batteries (Table 2.2). It is already possible to blend up to 50% SAF as a drop-in fuel in existing aircraft for some production pathways (Watson, 2024). However, high costs prevent rapid uptake and fossil jet fuel will still account for 70% of global aviation energy midcentury (Figure 2.9). Currently, hydro- treated esters and fatty acids (HEFA) refined from vegetable oils, waste oils, or fats into SAF are the only large-scale production pathway for bioSAF. However, feedstocks are limited, and estimates show that only 5% of total aviation fuel demand in 2030 can be covered by HEFA (WEF, 2020). We forecast that bioSAF will reach 4% in 2030 globally, led by Europe and North America. More production pathways will become viable, but bioSAF will still not reach more than about 30% of global demand because it is limited by the sustainable yield of biomass and competition for biofuels from other sectors (DNV, 2023).

Europe is the main advocate for moving beyond bioSAF to the next generation of synthetic SAF (electrofuels) which are currently much more expensive than bioSAF. Production volumes are constrained by limited access to both biogenic and atmospheric CO_2, and by renewable and low-carbon hydrogen. Production volumes will be small until the 2040s, reaching 4% of global demand in 2045.

Aircraft and airport fuel systems require modifications and retrofits to blend more than 50% SAF in fossil jet fuel. The industry has demonstrated that 100% SAF-compatible aircraft are possible and could be available as soon as 2030 (Collett-White, 2025).

However, the projected global SAF uptake globally does not warrant the need for such capabilities before 2050, and even then SAF will be the exception rather than the rule.

A truly zero-emission aircraft requires either hydrogen fuel cell or battery propulsion. However, these options require significant redesign of the aircraft – e.g. larger fuel tanks to store the less energy dense hydrogen or to integrate batteries. The infrastructure on the ground would also need modification. Further challenges come from their limited range: hydrogen propulsion is expected to be an option for short-to-medium-haul flights; only short-haul is possible by battery. Combined, hydrogen and electricity will grow slowly, from 1% in 2044 to 4% in 2056.

Aviation energy demand growth is met by low-GHG fuels

Final energy demand in aviation by carrier (Billion bbl/yr)

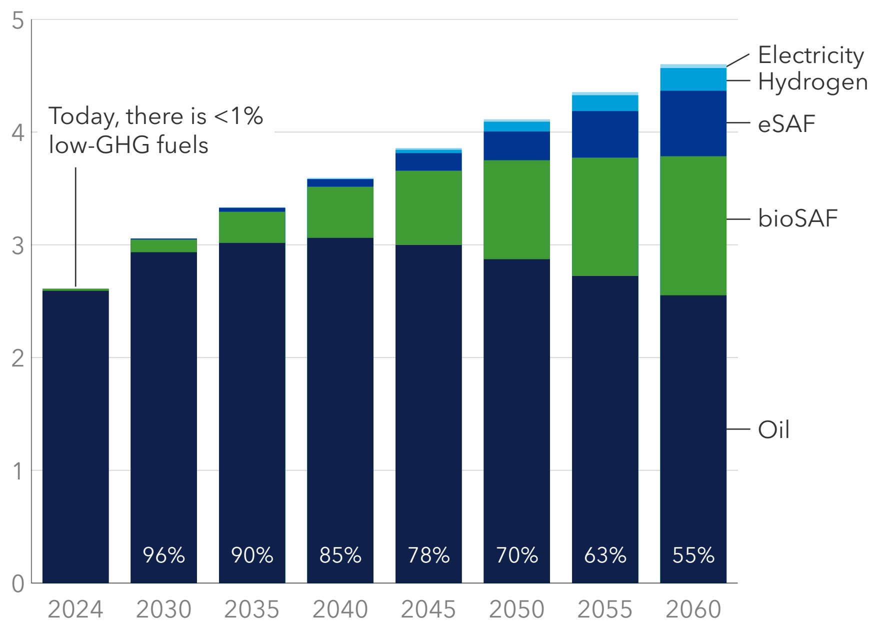


FIGURE 2.9 | Energy in units of barrels of Jet A-1 fuel, equal to 5.52 GJ. The percentages are the shares of fossil fuel.

Maritime

We forecast the maritime sector will cut its CO_2 emissions by 77% by 2050. While not fully 'net-zero by or around 2050', as per the goal of the International Maritime Organization (IMO), maritime looks set to decarbonize faster than all other transport subsectors.

This impressive abatement arises from a levelling off in demand for maritime transport from the 2030s, more efficient shipping, and a transition to low-GHG fuels and onboard CCS driven by the IMO' s Net-Zero Framework (NZF), approved in April 2025 (IMO, 2025).

The NZF is a binding international agreement and regulation. It uses a first-of-its-kind global carbon pricing mechanism to reduce GHG emissions from ships. Starting in 2028, ships will have to gradually reduce their well-to-wake emissions relative to a 2008 reference. The targets (a minimal 'Base' target and a more stringent 'Direct Compliance' target) will tighten towards 2040. Ship's that do not meet these targets must purchase remedial units from the IMO Net-Zero Fund or surplus units from ships that do. The cost for not meeting the minimal base target is USD 380/tCO_2. For more information, see DNV's *Maritime Forecast to 2050* (DNV, 2025).

Efficiency improvements are likely to remain the leading decarbonization strategy. Slow steaming is already common as a response to increasing fuel prices in the 2000s. Ship owners are now exploring a variety of additional solutions, including better routing based on weather forecasts (including AI-assisted weather routing), reducing drag by air lubrication or hull cleaning, and wind-assisted propulsion systems.

Shipping will also diversify its fuel sources (Figure 2.10). LNG is already in use, particularly but not only in LNG carriers, with slightly lower CO_2 emissions than oil. Electrification will be used (both port-side and via batteries), but is not an option for propelling deep-sea shipping. Biofuels will be the first low-GHG fuel in extended use, carving out a 4% market share by 2030, followed by e-methanol in 2037, and ammonia in 2039. Ammonia, though toxic, has the benefit of being carbon free. Over time, a significant share of ships running on oil, natural gas, and even biofuels will likely be retrofitted for onboard CCS. We project that 4% of emissions from ships running on fossil fuels will be captured by CCS in 2042. Nuclear propulsion is projected to become an option long-term, claiming a growing share in the 2050s. For more details and several different possible scenarios, see DNV's *Maritime Forecast* of last year (DNV, 2024b).

Maritime will decarbonize by both low-GHG fuels and CCS
Shares in final energy demand by carrier

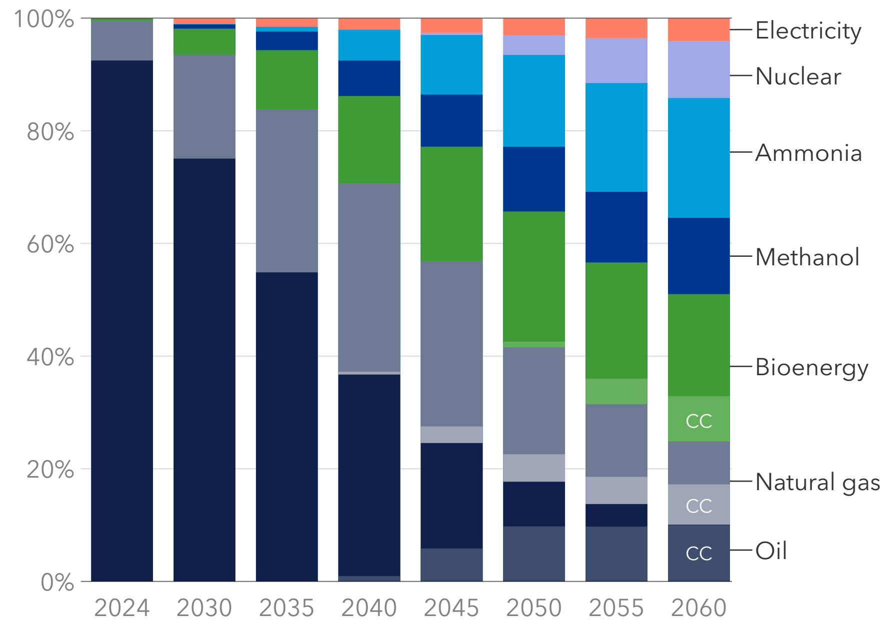


FIGURE 2.10 | CC: on-board Carbon Capture
Historical data: IEA WEB (2025)

Plateauing demand for shipping

Total demand for maritime transport in tonne-miles will grow by 10% by 2030, but will then plateau before slowly declining back to today's levels (Figure 2.11). This decoupling from global GDP, which is set to double by 2060, separates the maritime sector from all other transport subsectors. There are multiple contributing factors to this effect.

Shipping of fossil fuels will fall, cancelling other growth
World seaborne trade by segment (thousand Gt-nm/yr)

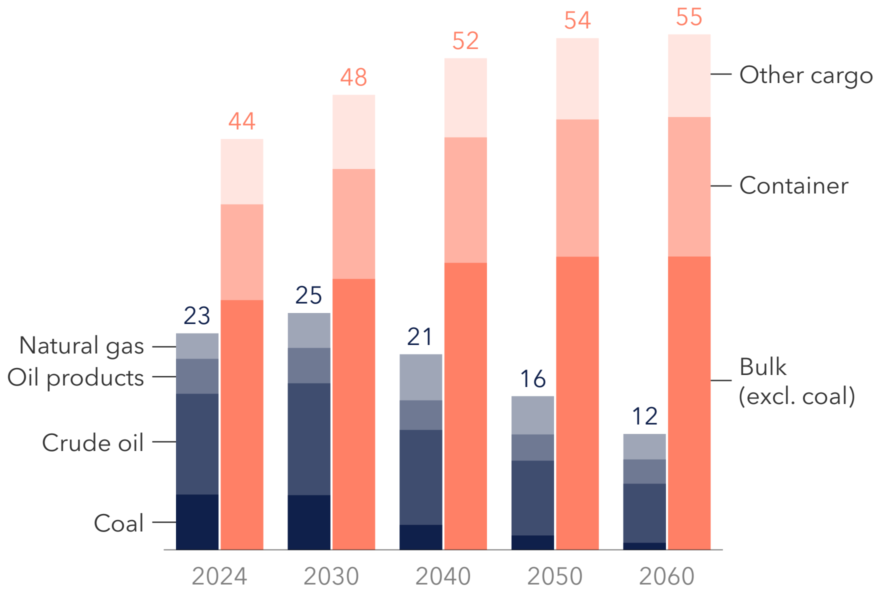


FIGURE 2.11 | Non-fossil oil products and alternative fuels are included in 'other cargo'. Historical data source: Clarksons (2025)

Ships mainly transport physical goods, not passengers or services. Future growth of the global economy will steadily become more service oriented: the economy will grow more than the production and shipping of goods (UNCTAD, 2024). Additionally, some production will be home-shored and some supply chains will become more localized, reducing the need for shipping of produced goods. This is being done to increase self-sufficiency and cut costs from more expensive fuels. On the other hand, recent conflicts like the war in Ukraine have disrupted trade patterns, leading to increased shipping distances, for example, for Russian oil.

Breaking it down into the separate shipping segments, the picture is more nuanced (Figure 2.11). Today, fossil cargo makes up one third of shipped goods. The transition to renewables will reduce the world's dependence on fossil fuels, and thereby the need to ship them, starting in 2030. However, the share of seaborne natural gas will temporarily increase significantly due to energy security and supply-demand patterns. Gas trade will almost double from today to 2040, before starting to decline. In contrast, container shipping will continue to grow, thanks to increased containerization and a growing economy. Non-coal bulk and other cargo will also grow, albeit to a lesser extent. The sum of non-fossil shipping will plateau in the 2050s, up about 25% from today.

2.7 BUILDINGS

A growing population and rising GDP per capita will put pressure on the buildings sector, expanding demand for both more floor space and additional energy for heating and cooling. We forecast that total buildings energy demand will increase by over 40% to 2060, but with big differences related to various end uses.

Supply side

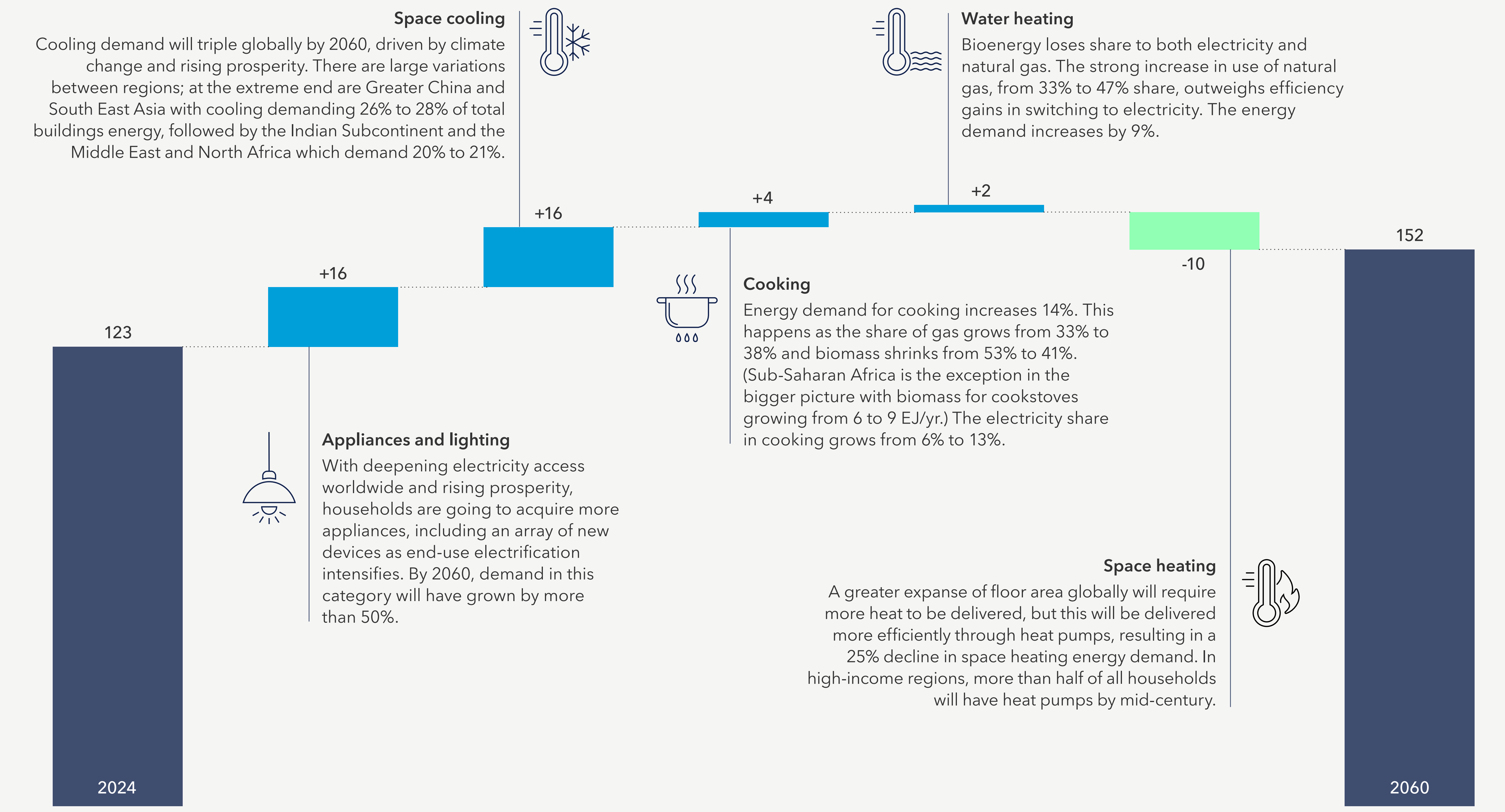
- Electricity supply to buildings will more than double by 2060. This increases electricity's share of energy demand to more than 50% by 2045 and more than 60% in 2060. Of this, 7% will be provided by behind-the-meter (self-generated) solar.

Demand side

- Space heating demand will be reduced by around 25% due to improved equipment efficiency, especially through increased use of heat pumps, but also due to a warming climate.
- On the other hand, demand for space cooling in buildings will more than triple to 2060 and require 14% of the total energy demand in this sector.

The drivers behind the increase of energy demand in buildings to 2060

Final energy demand by sector (EJ/yr)



Data center energy use is not shown on this overview, but is technically a part of buildings energy use. It will grow from 2 to 23EJ in the period.

Buildings energy demand

Buildings is forecasted to be the largest of our demand sectors in 2060 at 35% of global energy use, just ahead of manufacturing. It is also the only sector where we project continual increases in energy demand, from 124 EJ/yr now to 175 EJ/yr by 2060. The main drivers of this growing demand are rising affluence and a growing population. Natural gas and biomass use will persist but play a reduced role as the electrification of buildings advances.

Increasing floor area is the key driver of energy demand in this sector. With a growing world population, we expect commercial floor area to more than double and residential floor area to increase by around 50% by 2060. However, energy demand will not grow at the same rate thanks to efficiency gains from electrification, building insulation, and the influence of AI-assisted sustainable design on the architecture, engineering, and construction industry.

Electricity plays an increasingly central role

On-site combustion has been the primary means of serving many of the necessary functions in buildings, such as space heating, water heating, and cooking. However, electrified technologies – such as induction cooktops and heat pumps – are increasingly displacing conventional, combustion-based home appliances. Taking this and a continual increase in cooling demand into account, we expect electricity demand to grow from 45 EJ/yr in 2024 to 109 EJ/yr in 2060.

Data centres are one of the largest contributors to growing energy demand in the buildings sector due to the dramatic increase in adoption of AI by both consumers and companies. We describe our approach to calculating and forecasting data centre energy demand in Section 3.3.

Energy efficiencies and behind-the-meter are curbing total energy demand

New building technologies must offer the same level of convenience, if not better, while providing energy efficiency gains. Induction cooktops offer 30% or higher efficiency while having little impact on the use case compared with gas or electric coil stoves (Sweeney, Fortenbery, and Sharp, 2014). Electric heat pumps work fundamentally differently to other air conditioners and heaters by not generating heat but transferring heat into or away from the living space. Thus, they have the potential to provide more energy than is necessary to operate the unit. While conventional radiators and furnaces can be up to 95% efficient, heat pumps can be 350% to 450% efficient (GreenMatch, 2025).

However, it should be noted that a portion of any efficiency gains may be lost through a rebound effect. For example, owning an efficient heat pump could encourage users to increase the thermostat temperature, or use it on days they otherwise would not have as owners of older, less efficient heaters.

A moderate portion of the expected electricity demand increase will be met by behind-the-meter (BTM) generation – primarily rooftop solar with and without storage. We forecast 109 EJ/yr of electricity demand in buildings by 2060, of which 13 EJ/yr will be generated on-site. Cost saving will continue to be the primary motivator for BTM buildout in developed countries, while in developing countries the main factors impelling self-generation are energy access and reliability (see Section 3.5 for further discussion).

Appliances and lighting

In 2060, appliances and lighting will be the largest of our buildings end uses, at 25%. This end use is already completely electrified, with any marginal efficiency gains coming from improvements in end-use technologies. This subcategory is therefore likely to closely track increases in population and prosperity. Electricity demand from appliances and lighting will rise from 28 EJ/yr today to 45 EJ/yr in 2060. An increasing share of this energy will be self-generated electricity, which reaches 21% in 2060.

As described in the transport section, we expect a continual uptake in EVs. In our Outlook, electricity for EV charging is allocated to the transportation sector. In practice, however, most charging occurs at homes. This means electricity demand in buildings will rise significantly beyond what is shown under buildings in our results.

Space heating

We will see energy demand for space heating decline from 39 EJ/yr today to 29 EJ/yr in 2060 due to the decline in heating degree days (a measure of cold weather driving heating demand) in all regions and electricity displacing natural gas through the adoption of heat pumps. Heat pumps will rise from 5% of the technology mix today to make up 15% in 2060. Most heat pumps will be found in North America, Europe, China, and OECD Pacific, with marginal uptake in other regions.

Natural gas will still be the dominant energy carrier in space heating, although by 2060 its dominance will have reduced from its present 56% to 35% for the subsector. This decline can be partially attributed to gas boiler bans for new and existing buildings introduced in various European countries, Canada, Australia, and parts of the US. We project that by 2060, all regions will be at varying stages of phasing out new natural gas connections.

District heating also delivers efficiency gains, especially in urban areas, through economies of scale. Because a central hub can distribute direct heat to many households, it is more efficient than installing individual heating units (see Section 4.4 for further discussion). Most households in North East Eurasia are already heated with district heating due to legacy policies and Greater China has expanded the technology substantially in the north where there is the most heating demand. Some European countries are currently focusing on decarbonizing their already significant heating network in addition to further expansion.

Water heating

Water heating demand will rise from 22 EJ/yr today to 24 EJ/yr in 2060. The region with the highest energy demand for water heating will be Sub-Saharan Africa due to the dominance of less efficient biomass being used to heat water.

District heating can also provide hot water to buildings. Instead of installing an individual boiler per household, a heat exchanger can be used to transfer heat from the heating network to the building's hot water pipes. Similarly, combination units such as gas 'combi' boilers and air-to-water heat pumps can deliver space and water heating simultaneously.

Space cooling

Cooling degree days (CDD) will continue to increase in all regions towards 2060 as climate change intensifies – for example they will increase by 56% in Greater China and 21% in South East Asia. This increase drives up energy demand for space cooling, which will nearly triple globally from 9 EJ/yr today to 25 EJ/yr in 2060. The cooling demands for North America and OECD pacific will remain relatively stable as these two regions already have a high level of availability of cooling technology and a significant number of users are likely to switch to high efficiency air conditioning in the coming decade. All other regions will see an increase in cooling energy demand due to increasing affluence and CDD.

Some regions, such as Europe and the Middle East and North Africa, are exploring district cooling since it has similar economies of scale benefits as district heating.

Cooking

Energy use in cooking will increase 14% from 25 EJ/yr today to 29 EJ/yr in 2060. Despite a growing number of households, cooking energy demand will decline in higher income regions – namely North America, Europe, and OECD Pacific – as induction stoves are favoured over less efficient natural gas.

Biomass and natural gas will still be the dominant energy carriers for cooking in 2060 at 41% and 37% respectively, though electricity will rise from 6% of the mix to 13%, including self-generated electricity.

Sub-Saharan Africa will demand the largest amount of energy for cooking, 44% of the world total in 2060, due to the use of traditional biomass stoves burning fuels such as animal waste and wood. The Indian Subcontinent will demand the second largest share at 15%, but concerted efforts to reduce the use of traditional biomass in the region will successfully see the largest portion of this demand being met by natural gas. Programmes such as CARE India aim to transition households away from traditional cook-stoves to safer, clean-burning biomass stoves and gas cookers (SWITCH-Asia, 2019).

Heat pumps gradually replace gas boilers in most regions

Distribution of installed space heating technologies

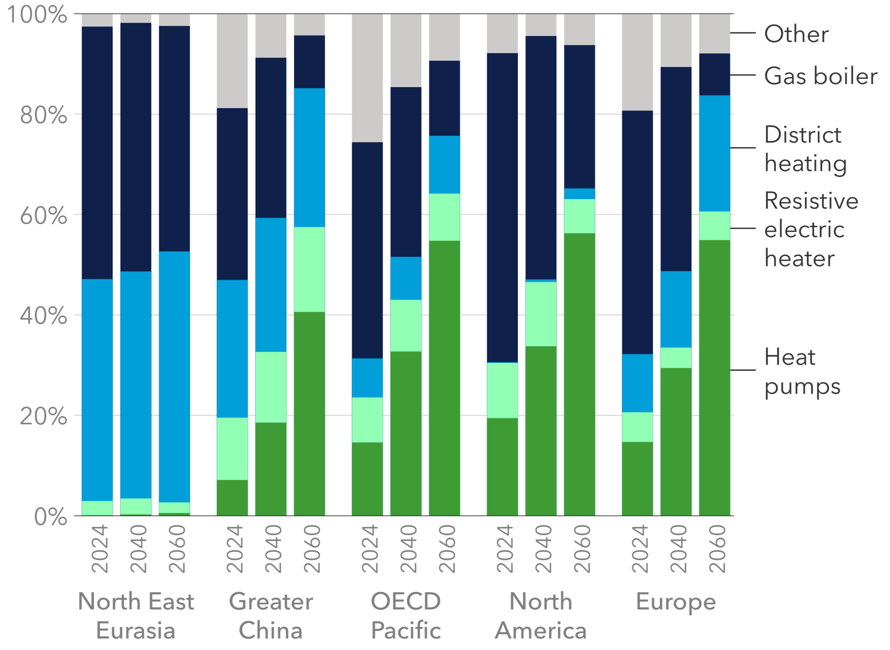


FIGURE 2.12 |

Increased efficiencies dampen the increase in energy demand

Buildings useful and final energy demand of various end uses (EJ/yr)

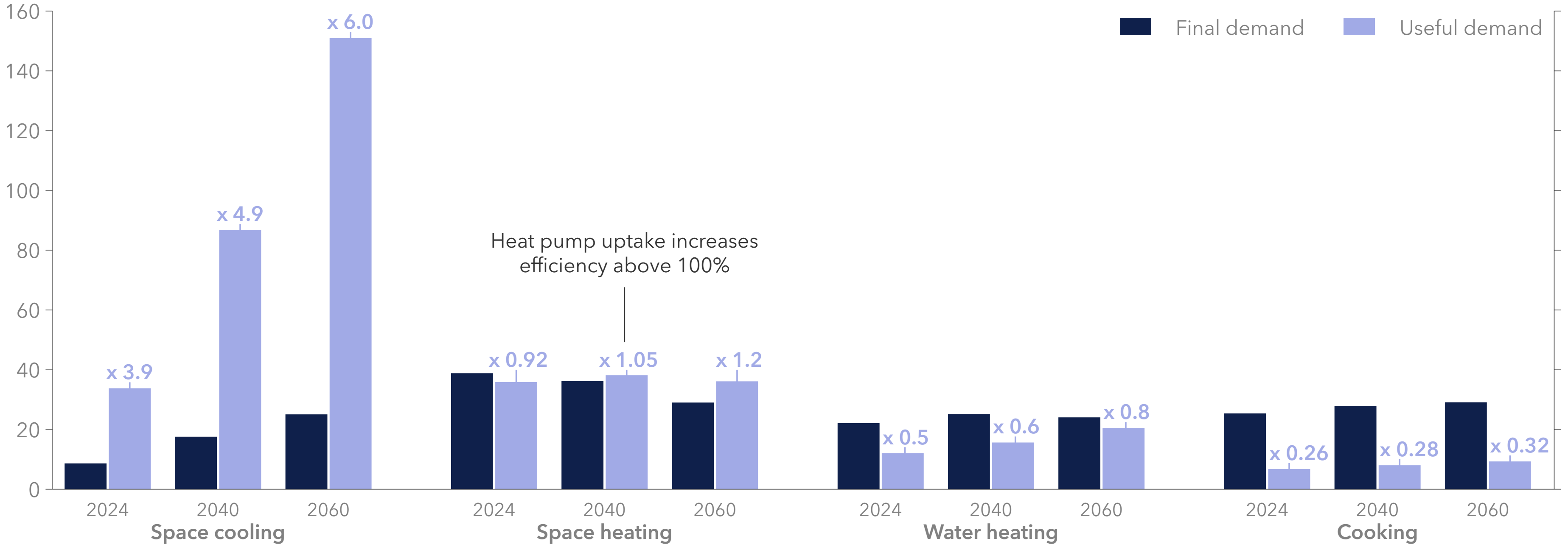


FIGURE 2.13 |

Electricity is the backbone for growth in demand

Buildings energy demand by carrier (EJ/yr)

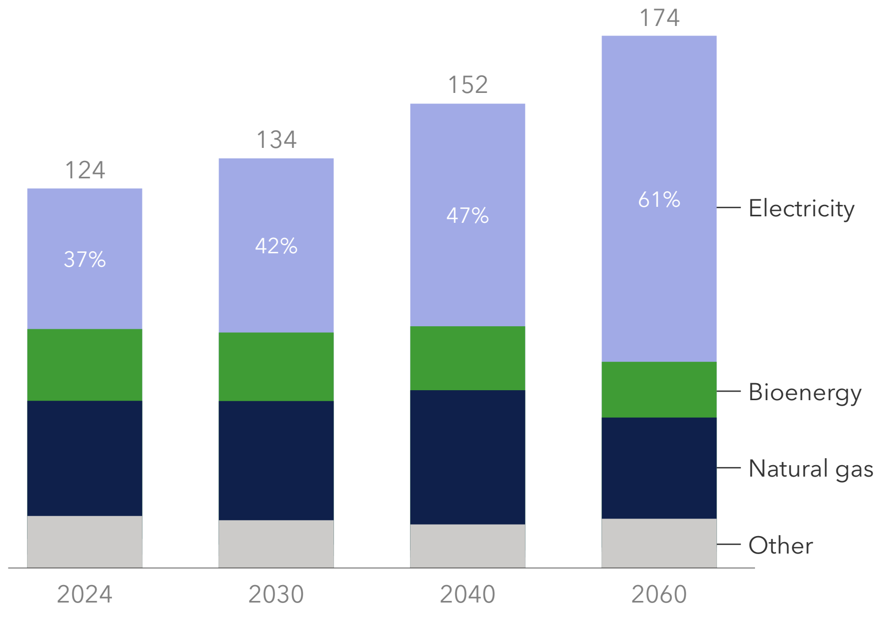


FIGURE 2.14 |

2.8 MANUFACTURING

Heavy industries struggle to decarbonize

Unlike in power and transport where emissions show a marked decline in the next five years, emissions in manufacturing will continue to increase in the next decade. Emissions will then start falling, but not as steeply as the other two sectors. In 2060, almost 40% of global energy-related and process CO_2 emissions will come from manufacturing, compared with 23% today.

This is mainly because manufacturing energy demand is dominated by a few energy-intensive heavy industries (steel, petrochemical, cement). Most new installations in these industries still rely on fossil fuel-based technologies. As these plants are capital-intensive long-term investments, we expect only moderate changes in the fuel mix during our forecast period.

Additionally, consumption of manufactured products will increase with the near doubling of global GDP and the world's population adding 1.6 billion people during our forecast period. This rise in manufacturing will be counterbalanced by efficiency gains and energy demand will plateau from the 2030s.

World CO_2 emissions by sector (Gt/yr)

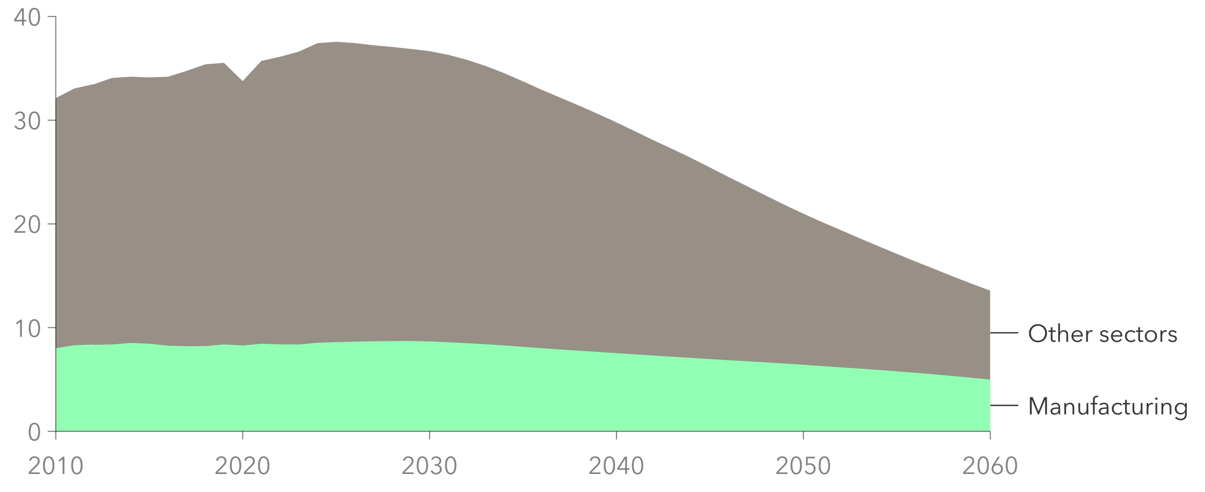


FIGURE 2.15 | Includes process emissions (e.g. cement calcination). Historical data source: IEA WEB (2025)

Decarbonization technologies pick up, but coal stays high

There is a diversity of technologies and processes in manufacturing that are often plant specific, with no one-size-fits-all decarbonization solution.

The sector therefore has a complex future energy mix. While manufacturing remains a significant emitter, it will also enable large-scale clean tech like hydrogen or CCS. From the 2040s, manufacturing will consistently be the largest sector for CCS, capturing 15% of the sector's remaining emissions in 2060.

Coal demand, as a traditional provider of high temperature heat, will decline more slowly than in other sectors. From one quarter today, manufacturing will represent about half of global coal demand by 2050. Yet manufacturing will also be the largest hydrogen user, representing more than 80% of global demand up to 2040 and making up 8% of the manufacturing fuel mix by 2060.

Final energy demand by carrier (EJ/yr)

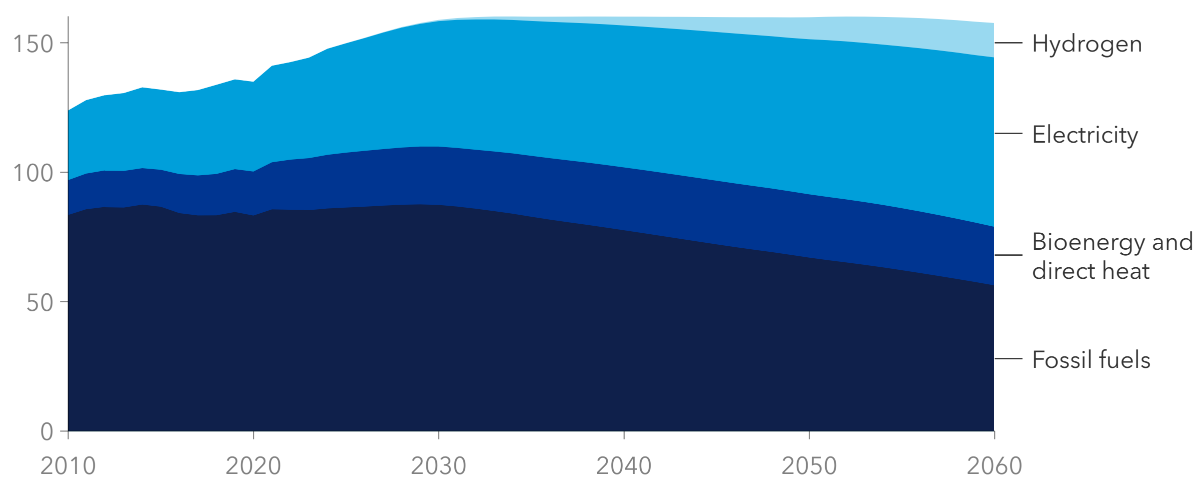


FIGURE 2.16 | Historical data source: IEA WEB (2025)

A regional shift driven by energy costs

These global trends are a composite of different sub-sectoral and regional dynamics. Energy consumption from manufacturing of goods, driven by increasing GDP per capita in all regions, will increase by 25%. In heavy industries, energy demand will still increase by 10% to 2030 before peaking and slowly decreasing by 0.3%/yr for the rest of the forecast period.

The coming decades will play out very differently across regions. Whereas OECD regions are stable, the Indian Subcontinent, followed by the other emerging regions, will experience the largest increase in manufacturing energy demand to serve both domestic and non-domestic markets and a persistent use of coal. China, with expanding electrification and a shift to higher value-added manufacturing, has a remarkable 32% decrease in manufacturing energy use. Nevertheless, China and the Indian Subcontinent will still represent two-thirds of coal demand by 2060.

Manufacturing energy demand (EJ/yr)

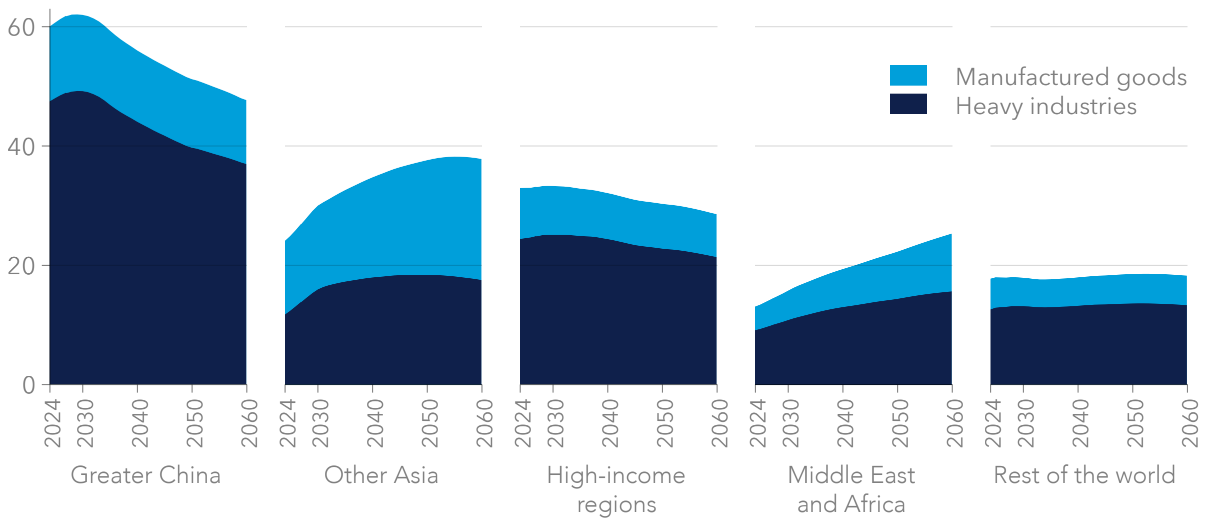


FIGURE 2.17 | Other Asia: South East Asia and the Indian Subcontinent.

Manufacturing energy demand

In the energy transition, manufacturing splits into two distinct energy and emissions pathways: energy-intensive heavy industry which is slow to decarbonize; and lighter manufacturing, which has more flexibility and can decarbonize faster through electrification. Heavy industry tends to follow low-cost energy across the globe, reshaping trade flows, although there are exceptions to this (e.g. cement plants located close to sources of demand like large cities). Energy costs are less decisive for lighter manufacturing and not as important as the availability of productive, skilled employees, robust national ICT infrastructures, and conducive trade and domestic policies. However, goods manufacturing, particularly more automated energy intensive plants, is still sensitive to electricity prices and carbon policies.

Heavy Industry: a future of continued emissions and fossil fuel reliance

Heavy industry consists of hard-to-decarbonize sectors, like steel, chemicals, cement, and aluminium production. Reliance on massive-scale production and high-temperature heat, combined with unavoidable process emissions, makes decarbonization difficult.

The core challenge for this sector is that energy is not just an operational cost but a primary driver of competitiveness, making manufacturing location highly sensitive to energy prices and climate policy. This policy evolution, combined with the technical hurdles of replacing fossil fuels and deploying CCS, means that under expected policies, heavy industry will remain a major source of global CO_2 emissions for decades to come.

Decarbonizing these sectors is a daunting task, and the approach to climate policy is evolving. Historically, governments have shielded these strategically important, trade-exposed industries from the full cost of climate action to prevent 'carbon leakage', a scenario where companies move production to regions with weaker climate policies, slowing down net global emissions reduction. The primary tool for this protection has been granting free emissions allowances in carbon markets.

Now, however, industries are entering a new phase. The introduction of more robust carbon pricing and innovative policies like the EU's *Carbon Border Adjustment Mechanism* (CBAM) represents a critical test. These measures are designed to level the playing field by imposing a carbon cost on imports, forcing a real confrontation with the economics of decarbonization.

The coming years will reveal whether it is possible to impose these costs without simply driving industry elsewhere. Our view is that in a more deglobalized world, regions will take protective measures to maintain sufficient levels of domestic production, partially shielding heavy industries from competition in the global market.

While China's demand for primary materials is maturing, leading to a peak in its energy use, the medium-term centre of growth is moving to the rest of Asia. We forecast this region will account for most of the growth in energy demand from heavy industry to 2040. In contrast, high-income countries will see a continued decline in their share of global production.

Energy is less decisive for manufactured goods

The manufactured goods subsector is more dynamic and diverse, characterized by lower energy intensity and a greater reliance on electricity. The energy story for this sub-sector is primarily one of continued electrification and efficiency. Its fuel mix is already significantly different from heavy industry. Today, electricity provides over 40% of its energy needs, with natural gas and bioenergy products making up most of the remainder. Our forecast shows this trend continuing with electricity's share above 50% by 2060.

Below this seemingly small increase, every MWh will provide more in manufactured goods. Automation and digitalization will continue to improve efficiency. Electrification of low-to-medium temperature heat is emerging, facilitated by maturing technologies like industrial heat pumps. Consequently, the decarbonization pathway for manufactured

The **cement** industry exemplifies the problem of process emissions. Roughly two-thirds of its emissions are not from fuel combustion but are released directly from the chemical process of calcination, where limestone is heated to produce lime. This makes deep decarbonization impossible without CCS, as switching fuels can only address about a third of the total emissions.

The **chemicals** sector faces a different, but equally complex, challenge: the dual role of fossil fuels as both an energy source and a primary feedstock. The production of high-value chemicals like ethylene and propylene relies on hydrocarbon inputs, meaning decarbonization requires replacing both the energy source and the raw material. Alternatives like bio-based feedstocks or advanced recycling face significant cost and scale hurdles.

The **steel** sector, the largest single consumer of energy in manufacturing, will make important, but by no means comprehensive, decarbonization gains. The sector faces its own unique set of technological challenges, which we detail later in this section.

Iron and steel will be the only heavy industry with significant change in fuel mix

Final energy demand by subsector (EJ/yr)

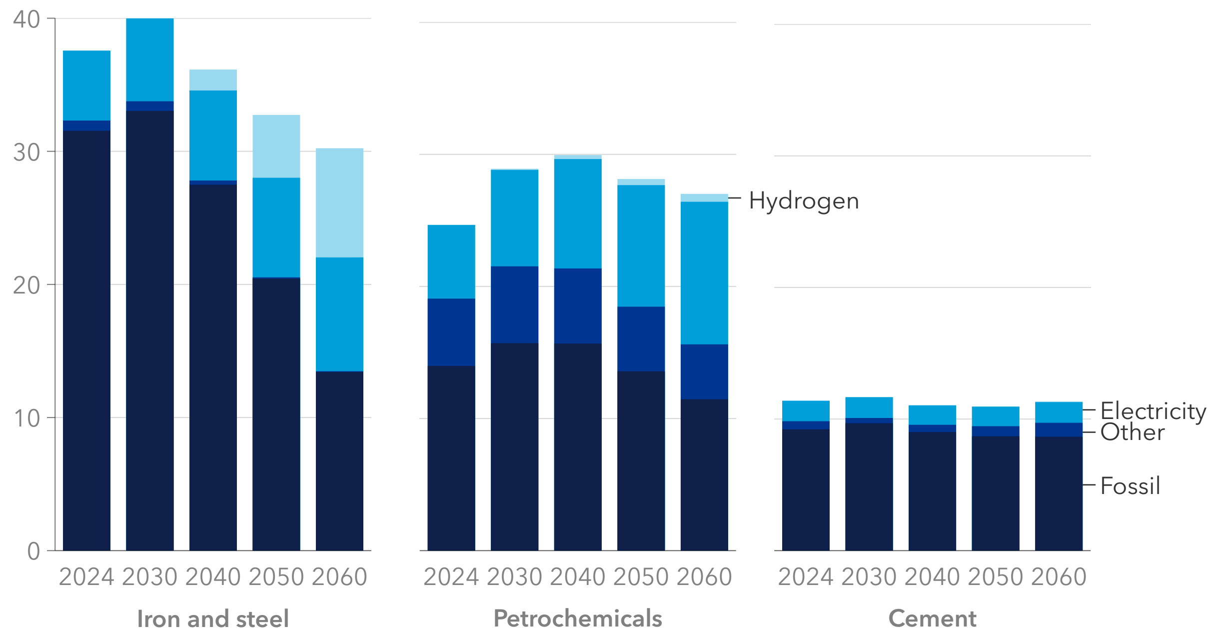


FIGURE 2.18 |

goods relies more on a greening electricity grid than on breakthrough technologies like CCS.

The regional breakdown for manufactured goods is also distinct. Unlike heavy industry, its location is driven more by proximity to consumer markets and skilled labour than by energy costs. This results in a stronger presence in high-income economies and less susceptibility to large-scale geographic shifts.

High-income countries and Greater China together account for half of the energy consumed in this sub-sector. This reflects their dominance in complex value chains like automotive, machinery, and electronics. While we do not forecast a major rebalancing, growth is fastest in emerging economies. For example, the Indian Subcontinent will see its energy demand from manufactured goods grow by 3% per year in the next decade as it expands its role in the global markets.

While much policy attention is focused on the global competition for advanced manufacturing – spurred by initiatives like the US *Inflation Reduction Act* and EU *Chips Act* – it is important to place this in an energy context. These high-value-added sectors, while strategically critical, represent a very small fraction of total manufacturing energy use. Their geographic shifts, therefore, have little impact on the global manufacturing energy balance. The core of the energy transition challenge remains firmly rooted in heavy industry.

Electricity, decisive despite low penetration

Electrification, both direct and indirect, is the primary technical solution to decarbonizing manufacturing and increasing energy efficiency. Electricity prices and resources will be among the major factors restructuring the global industrial landscape.

The next decade will be one of growth for electricity in manufacturing. In just ten years, total industrial electricity demand will increase by 25%, or 3,000 TWh. The growth will significantly slow down after that, with only 1,500 TWh of additional demand in the 2035 to 2045 period. This decade is crucial, and light and heavy industries will face different challenges.

Electricity and bioenergy greening manufacturing goods
Final energy demand (EJ/yr)

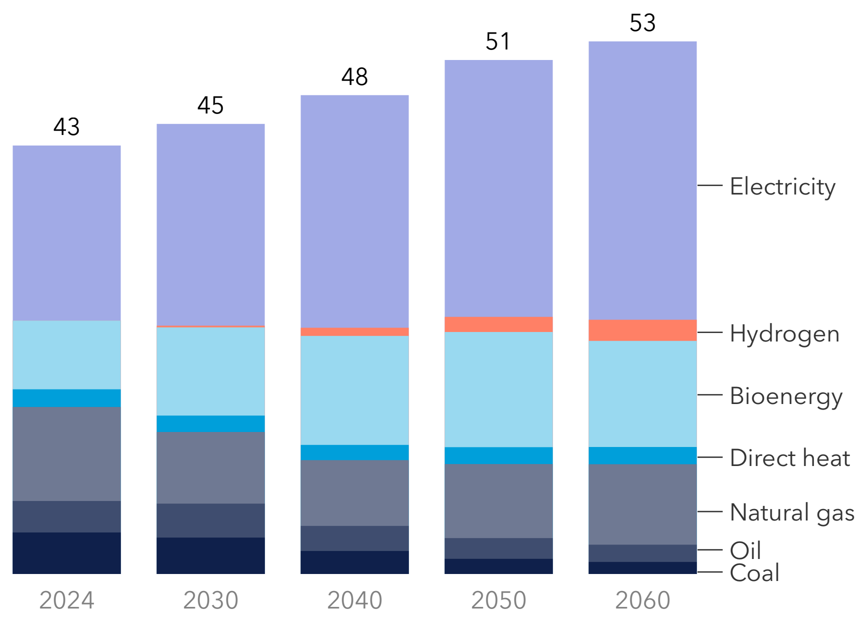


FIGURE 2.19 | Small amounts of geothermal and direct solar energy not shown.

There will be clear regional differences in prioritizing manufacturing in the next decade (Figure 2.20). The Indian Subcontinent and Sub-Saharan Africa are set to allocate the largest shares of their new power generation to the industrial sector. This signals a clear strategy to leverage manufacturing for broad economic development.

In contrast, manufacturing in North America and Europe must compete more fiercely for a share of new generation. Internal regional competition between new users is one of the key drivers of higher electricity prices for industrial users. Data centres, led by AI uptake, will be a big competitor to other industries. For North America, we project demand from data centres to grow by almost 700 TWh in the next decade while manufacturing will only grow by 15 TWh, a mere 1% of the growth in electricity demand. In contrast, decarbonization goals in Europe and protection measures like CBAM mean that industries will get a higher priority and better access to additional generation.

An additional challenge is that unlike globally priced fossil fuels, electricity markets are highly localized. This means electricity price has a disproportionate impact on competitiveness on heavy industries, even when electricity is not the largest component of the energy mix. For heavy industries with thin margins, this regional variation in power prices can be the deciding factor in their viability. Even for cement, where electricity represents only around a sixth of the energy demand, a difference of USD 100/MWh (like we have seen between Europe and other regions) leads to additional 20% of production costs. As a result, high price volatility has a negative impact on future investments.

The impact of this competition will not be felt evenly, as the global picture for industrial electricity prices will not change dramatically in the next decade. We forecast that industries in Greater China and the Indian Subcontinent will continue to benefit from cheaper, state-supported electricity. They will together add four times more electricity demand than their counterparts in Europe or North America in the next decade.

Although they are more reliant on electricity, light industry like goods manufacturing can often absorb higher energy costs. These costs represent a much

Manufacturing's varying electricity regional priorities
Share in additional electricity demand, 2024–2034

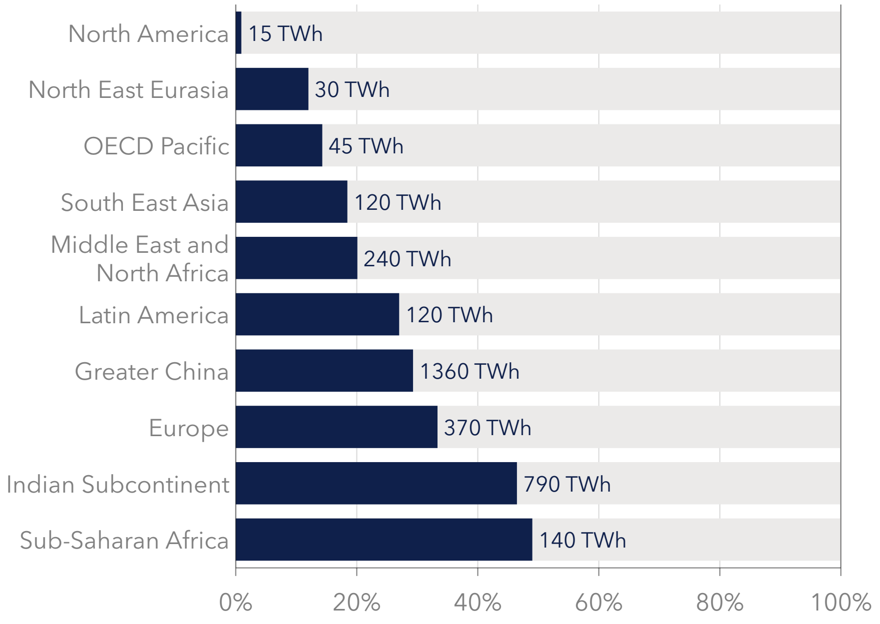


FIGURE 2.20 |

smaller fraction of their operational costs, and products are not commodities but rather higher value-added products. For these industries, other factors like access to a skilled workforce, infrastructure, or industrial policies, will play a larger role. However, securing stable, long-term supply is a base need. This challenge will also be present in heavy industry, particularly for investment in new electricity-intensive plants like electric arc furnaces.

The competition for cheap electricity is amplified by the rising demand for energy intensive hydrogen, which is essential for decarbonizing high-heat processes. The cost of electrolysis-based hydrogen is indeed directly tied to the price of the electricity used to make it. Our forecast shows a wide divergence in hydrogen production costs, doubling from less-advantaged areas to regions with optimal renewables (Section 4.1). Natural-gas based hydrogen with CCS will provide an alternative in gas-producing regions. This creates another energy-driven field of competition that will further decide the winning regions in the future of decarbonized heavy industries.

Steel at the crossroads of the energy transition

Steel production involves all the challenges of the industrial energy transition, and every major decarbonization pathway is in direct competition. Global steel demand is set for slow growth in the coming decades, rising from 1.9 billion tonnes today to just over 2 billion tonnes by 2060. Behind this apparent stability, both the location and the production routes will experience significant transformation. Direct emissions from steel production will more than halve by 2060, from 2.8 to 1.1 $GtCO_2$/yr.

The most energy-efficient method, recycling scrap steel in electric arc furnaces (EAFs), is constrained by the finite global supply of scrap. Our forecast shows that its share will more than double from 23% to 50% of global steel production by 2060.

Although recycling will grow significantly, energy-intensive virgin steel production will still need to account for over 50% of total output in 2060. The world's fleet is currently dominated by the coal-based blast furnace-basic oxygen furnace (BF-BOF) route, representing 70% of production. From the 2030s, BF-BOF installations will meet hard competition from the rising scrap-based materials, and their share will drop to 20% at the end of our forecast period.

Direct reduced iron (DRI) is the competing technology for primary (virgin) steel production. This is an already proven technology with coal or natural gas, representing 7% of global production today, mostly located in the Middle East and in India. The hydrogen route carries the promise of decarbonized production. However, the number of FIDs for large-scale projects remains critically low compared with stated country and corporate ambitions (GEM, 2025). High hydrogen costs will delay uptake to the mid-2030s. In the meantime, natural gas will supply most of the new DRI additions.

CCS appears to be an attractive option for retrofitting existing, long lifetime blast furnaces. However, with low CO_2 concentrations and complex fume treatment, the cost will be high. Therefore, we expect a very limited uptake in a few selected projects.

The future of steel production will be determined by a complex equation of regional cost and availability of four key inputs: high-quality scrap, natural gas, clean electricity and green hydrogen, and viable CCS infrastructure. New procurement regulations and market demand mean that carbon intensity will eventually become a part of the equation as critical as the quality of the final product.

Regional resource advantages will dictate which path is chosen:

- **Greater China** will continue being the world's largest steel producer to 2060. However, the region is dealing with a peak of domestic demand, and major overcapacity issues. This means that it will be locked in with its relatively young fleet of energy-efficient BF-BOF plants for the coming decades. In that context, DRI-H_2 production only really picks up from the 2040s.
- **High-income & scrap-rich regions (e.g. Europe, North America):** These regions will maximize scrap recycling, with EAFs projected to grow from 50% to over 75% of their production by 2060. For the remaining virgin production, blast furnaces will continue to struggle with global competition and close. High hydrogen costs have led to a series of cancellations for DRI-EAF projects in the past year. This route will eventually pick up, but only partially replace the BF-BOF production.
- **Gas-rich regions (e.g. Middle East, also North America):** These areas are positioned to continue leading the production of natural gas-based DRI. We forecast gas-based DRI-EAF production in the Middle East will triple by 2050.
- **Growth Regions (e.g. Indian Subcontinent, South East Asia):** Facing the largest increase in demand and low scrap availability, these regions must build new primary steel capacity. Despite the risk for lock-in, the list of committed projects shows that major additions will be made to the BF-BOF capacity in the medium term.

Steel production technology depends on regional context

Steel production in selected regions (Mt/yr)

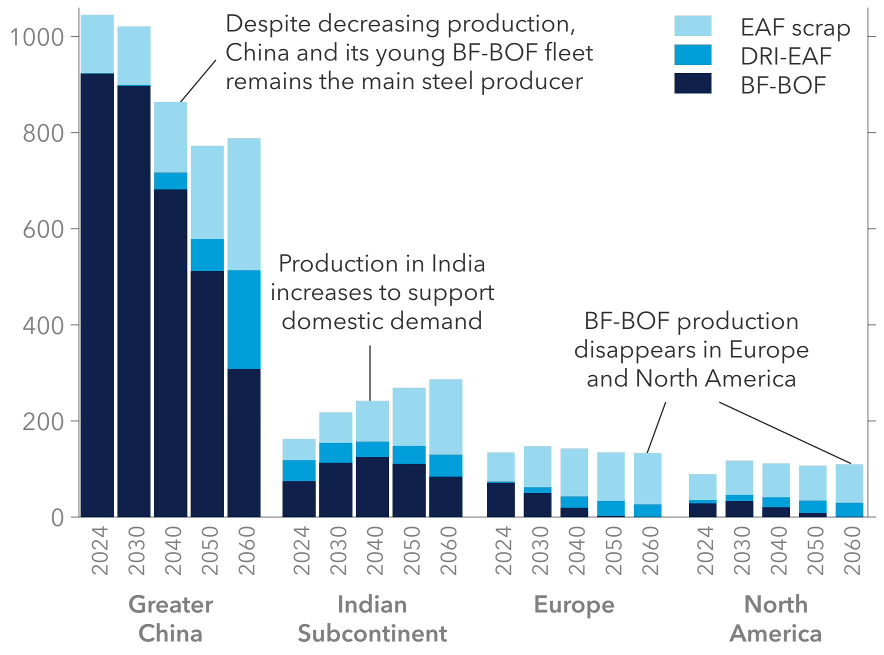
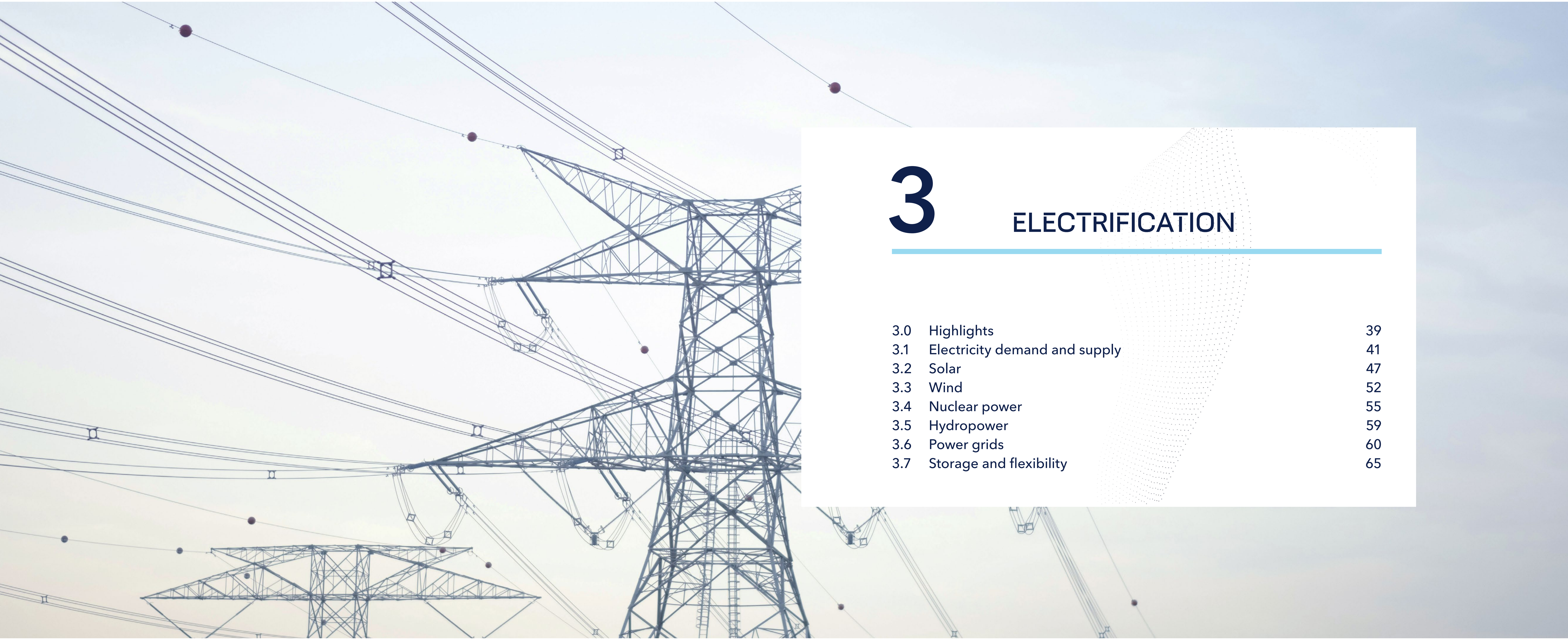


FIGURE 2.21 | Historical data source: World Steel (2025)



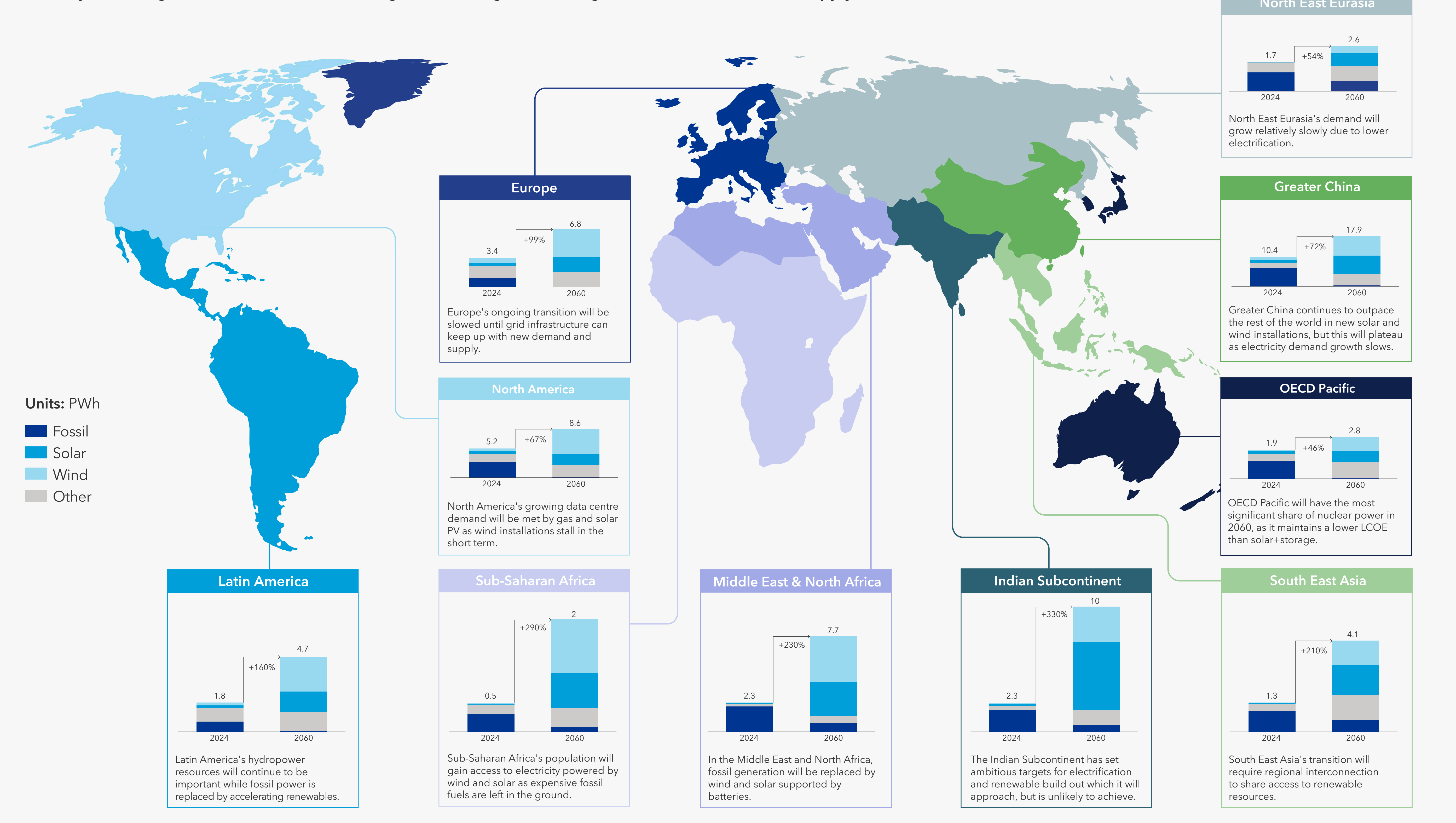
3 ELECTRIFICATION

3.0 HIGHLIGHTS

Electricity demand grows and supply greens globally

- By 2060, global electricity demand will have increased by 140% and electricity supply will be 96% decarbonized. This growing and greening will be responsible for most of the decline in energy-related CO_2 emissions from 2025.
- Total electricity demand will grow faster in the Global South as populations increase, develop, and achieve universal energy access. These regions will more than quadruple their demand while more developed regions will double theirs. Their increases will be due to EV uptake and electrified heating, cooling, manufacturing, and hydrogen production after the 2030s.
- Each region's supply mix reflects their available resources, decarbonization ambitions, and demand profiles. Solar and wind will generate most electricity in all regions in 2060, with a global share of 47% and 32%, respectively.
- More developed regions will have more diversified and decarbonized energy mixes towards 2060. Regions that must continue to develop as they transition will depend on fossil fuels further into the future.

Electricity demand grows most in lower income regions while high income regions have more diversified supply mixes.



3.1 ELECTRICITY DEMAND AND SUPPLY

Global electricity demand is set to more than double over our forecast period.

Demand

Worldwide demand rises from 32 PWh/yr in 2024 to 77 PWh/yr by 2060. These numbers include the energy sector's own use and transmission and distribution (T&D) losses (Figure 3.1). The surge in demand is driven by increased electricity use in buildings, including data centres, and the accelerating electrification of transport and industrial processes.

The expansion of electricity consumption reflects deep structural changes across energy demand sectors. By 2060, we expect the global **EV fleet** to have reached 3.3 billion vehicles, requiring around 9 PWh/yr. EV adoption is one of the primary sources of demand growth in North America, Europe, and the OECD Pacific, where electrification in other sectors is already advanced.

In **industry**, electricity powers the machines and equipment central to modern manufacturing. In rapidly industrializing economies such as India and Indonesia, rising mechanization is steadily increasing electricity demand as manual processes are replaced with automated, energy-intensive systems. Additionally, the uptake of electric heating – particularly industrial heat pumps – is boosting electricity use in low- and medium-temperature processes across sectors like food processing, textiles, and chemicals.

In **buildings**, demand is being driven by population growth, urbanization (where electricity replaces other energy sources), and higher living standards. Electricity supports a wide range of daily needs, from lighting and refrigeration to appliances and entertainment. While efficiency gains – such as the adoption of LED lighting – are helping to limit consumption in some areas, new demand is emerging. In the Global South, a sharp increase in air conditioning use will add 7 PWh/yr by 2060. In colder regions, we expect the widespread use of heat pumps to become the main heating source in about a third of households and demand another 1 PWh/yr. Although they add to electricity demand, heat pumps are far more efficient than the systems they replace: for every unit of electricity used, they deliver two to four units of heat – much more than electric heaters – and they also require less energy than oil or gas boilers.

Data centres currently represent a small but growing share of global electricity use, consuming around 0.4 PWh/yr, or 1.3% of total demand, mostly for non-AI applications. However, the AI boom is driving the construction of larger, more energy-intensive facilities. New AI-focused data centres can consume up to ten times more electricity per rack than traditional ones (Economist, 2025a). By 2060, we expect AI to account for 78% of total data centre electricity use, pushing overall demand in the sector to 6 PWh/yr – 9% of global electricity consumption. Data centres will be the biggest growth driver of electricity demand in North America. (See fact box on page 45 on Data centre and AI energy demand).

Hydrogen production is also emerging as a significant source of electricity demand, especially in regions with abundant renewables such as Europe, the Middle East and North Africa, and the OECD Pacific. By 2060, we expect grid-connected electrolysers will use 6 PWh/yr of electricity. This trend is helping to establish a new dynamic in the energy system where renewable generation and flexible electricity applications like hydrogen production evolve in tandem and reinforce each other's growth.

Buildings and transport drive electricity demand to 2060
Change in world annual electricity demand (PWh/yr)

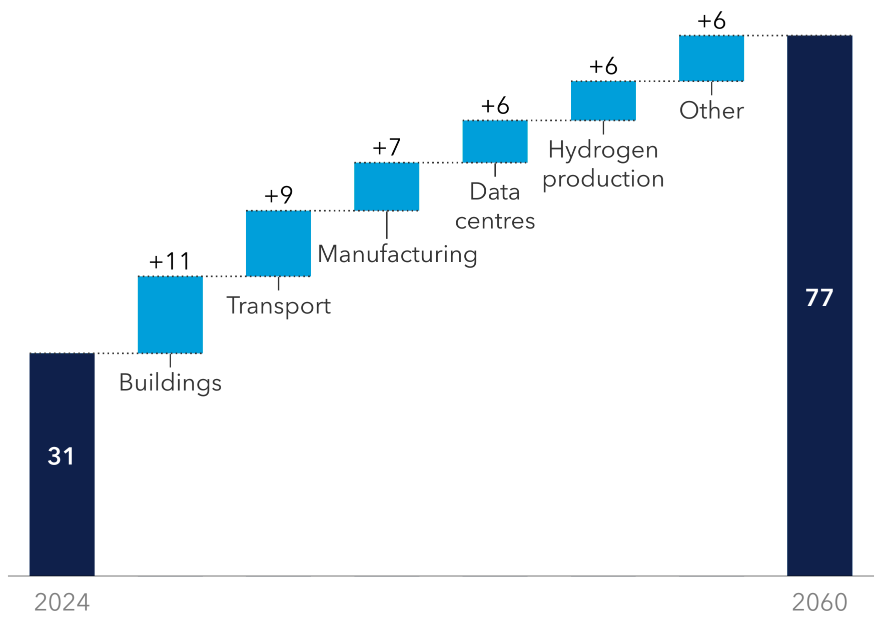


FIGURE 3.1 | Other includes energy sector own use and T&D losses.

Supply

Renewables will supply most of the growing global electricity demand, but fossil-fired plants will still be in the supply mix past 2060.

The path to solar supremacy

The future of global electricity generation is variable renewable energy sources. Of these, solar and, separately, solar+storage are the two largest, generating 50% more power than onshore and offshore wind combined in 2060. In most regions, solar plants are the cheapest and quickest new energy sources to build and are widely available for residential and commercial installations. At all scales, the addition of batteries enables shifting the hours of available electricity to optimize supply and decreases the payback period for the investment.

In 2024, growth in electricity demand (+1,800 TWh) outpaced growth in non-fossil electricity generation (+1,085 TWh). Renewable generation will only begin to decrease emissions when it exceeds new demand. This milestone is referred to as 'additionality' and will be achieved globally in 2025, but in different years regionally.

Europe and North America passed this milestone in 2007, followed by OECD Pacific in 2013, Latin America in 2015, and Sub-Saharan Africa in 2016. Greater China will be the next region to reach additionality in 2025, while South East Asia and the Indian Subcontinent will take until around 2030. Finally, the Middle East and North Africa and North East Eurasia will reach additionality after 2040.

Coal, oil, and gas exit still out of reach

The end of coal-, oil-, and gas-fired electricity remains outside the temporal scope of our forecast. However, we expect peak emissions from fossil-driven electricity production in 2025 and a modest drop in electricity supplied by fossil fuels in 2026. It is no coincidence that 2025 will also mark the peak of Greater China's coal-generated electricity. The region accounted for 58% of coal-fired generation in 2024. The Indian Subcontinent was the second largest consumer of coal-generated electricity in 2024 and their consumption will not peak until around 2030.

Over the coming decades, gas-fired plants and some coal-fired plants will increasingly be used primarily for back up and flexibility. Fossil-generated electricity will decrease faster than installed capacity, leading to higher costs per unit of electricity. From 2030 onwards, flexibility in the energy system will increasingly be supplied by storage.

By 2060, only 4% of electricity will be supplied by fossil fuels, though this is not globally uniform. The Middle East and North Africa, North East Eurasia, and South East Asia will source significantly more electricity from fossil fuels than the global average, while North America, Latin America, Europe, Greater China, and the OECD Pacific will virtually phase out fossil fuels by the end of the forecast period.

The comeback of nuclear and the stasis of hydropower and geothermal

Nuclear energy's contribution to electricity generation has been trending gradually downwards since 2000, from 17% to 8% in 2024. Generation has been almost flat for 25 years and not kept pace with increasing electricity demand. Driven largely by energy security concerns, we see an increase in nuclear-friendly policies, especially in Europe and North America. However, due to the long construction timelines for reactors, most regions will not see a significant increase in nuclear generation until the 2040s. Exceptions include Greater China, OECD Pacific, and the Middle East and North Africa, where construction on the next generation of conventional nuclear reactors is already underway and we expect generation growth before 2030. We expect the first generation of small modular reactors to materialize in the next few years and, towards the end of our forecast period, are potentially be less expensive and quicker to build than conventional reactors (IEA, 2025a). Overall, we see nuclear generation expanding by 150% between 2024 and 2060, slightly faster than the rate of global electricity demand over the same period (+140%).

Electricity supply greens and grows

World electricity generation (PWh/yr)

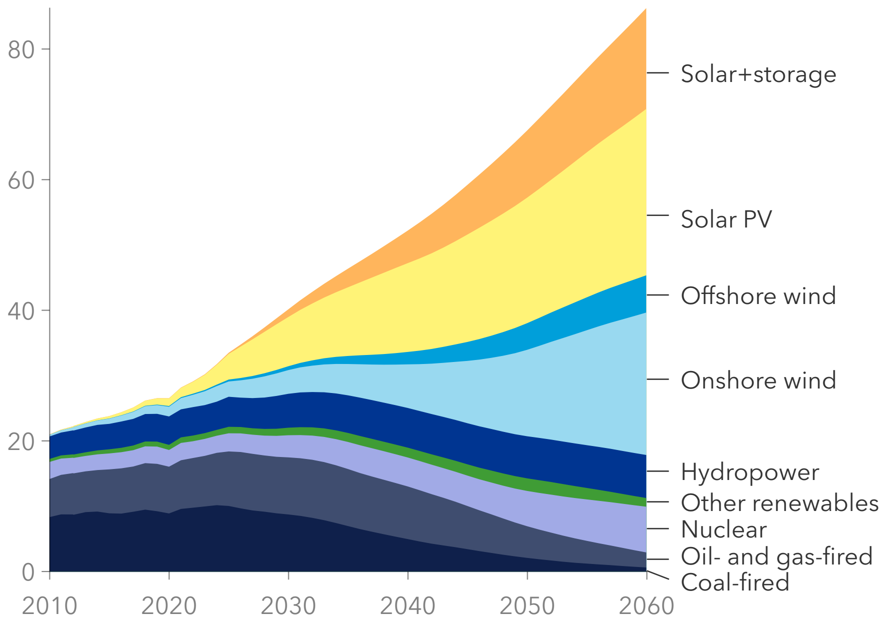


FIGURE 3.2 | Generation includes behind-the-meter and off-grid.
Historical data source: IEA WEB (2025), GlobalData (2025)

The absolute generation of hydropower, geothermal, and bioenergy will generally increase over the forecast period, but at a lower rate than the overall increase in electricity demand, leading to a declining contribution to the energy mix. Siting new capacity will be a challenge for new hydropower, particularly into the 2030s and beyond. Increasing drought and flood occurrences, the result of changing rainfall patterns due to climate change, make hydropower a less reliable energy resource (World Economic Forum, 2023).

A whole new power system

The electrification shift is not simply a matter of replacing fossil fuels with electricity; it marks a systemic transformation of the power sector. New demand patterns from electrified transport and industry will increase peak loads, shift consumption profiles, and require major infrastructure upgrades. At the same time, declining costs of solar, wind, and battery storage will enable renewables to dominate the electricity supply. The result will be cheaper, more readily available electricity produced closer to consumers, but the system will require new, more complex management.

Grid flexibility will be vital for balancing new demand patterns. EVs, for example, will act as both large, flexible loads and distributed storage via vehicle-to-grid (V2G) technologies. We project the aggregate impact of these dual functionalities to account for approximately 3% of total electricity demand (excluding T&D losses) by 2060. At the same time, the spread of rooftop solar, battery storage, and smart charging is turning consumers into 'prosumers', contributing to a more decentralized and responsive electricity system (see Behind-the-meter on page 50). By 2040, such decentralized sources will supply around 9% of total electricity demand (excluding T&D losses), with the share reaching 13% by 2060.

From the 2040s, the bulk of energy supply will be variable renewables, for which the intrinsic time of generation does not always match peak demand. To overcome this mismatch, renewable electricity must be 'firmed'. Short-term storage can shift power from solar's generative daytime hours into demand-intensive evenings, while long-term storage can overcome weeks where the sun does not shine and the wind does not blow. By 2060, short- and long-term storage demand will account for 9% of total electricity demand.

For consumers to fully reap the benefits of low-cost renewables, electricity markets will need to introduce time-of-use pricing, automated demand response, and incentives for flexibility. Well-designed pricing mechanisms, such as rising block tariffs (which set a low price for an initial 'block' of essential consumption, then progressively higher rates for additional use) and time-of-pricing (charges more during peak demand hours and less when the grid is less stressed), can promote efficiency and support social equity by protecting low-income users while encouraging heavier consumers to invest in energy-saving technologies. Ultimately, consumers need to see the benefit of electrifying their energy end-use; which at the very least, should result in significant efficiency savings, even if regulators do not ensure the low cost of renewable generation is reflected in the per-kilowatt tariff.

While nuclear, hydropower, and gas will continue to provide the final units of electricity, and often set the price, the number of hours each year when fossil fuels are needed will steadily decline.

Power system change driven by economics

The levelized cost of energy (LCOE) is the main metric used to compare the economics of the components of the energy mix. It measures the average cost of producing electricity over the lifespan of a generating asset. We adjust our LCOEs first by policy subsidies and tax mechanisms, including carbon prices, and second by each source's average energy revenue (the demand of each electricity source at the time of its peak generation).

The LCOEs of fossil-fired power plants trend upwards over the coming decades. As their use reduces, the cost per unit of generation goes up. In addition, carbon prices will rise. As a combination of these two factors, coal's LCOE will triple by 2050 and natural gas's LCOE will double by 2060.

In contrast, the accelerated installation of variable renewables has led to a steep decline in their LCOEs as learning rates take effect on both capital expenditure (CAPEX) and operational expenditure (OPEX). Despite recent supply chain challenges, we expect fixed offshore wind to be the next technology to experience falling costs in tandem with annual installations tripling between 2024 and 2030.

Despite solar PV being the least expensive energy source to install, its energy revenue-adjusted LCOE is above that of onshore wind. This is because solar PV's peak generation period, summer days, does not align with high energy demand, making the average revenue the lowest of all energy sources. When paired with battery storage, the ability to shift generation hours into the evening increases revenue.

The LCOEs of nuclear, hydropower and bioenergy generally trend downwards due to learning rates. Hydropower's capacity is dominated by fewer, larger projects, leading to comparatively volatile global LCOE. Bioenergy's LCOE increases dramatically in the 2050s due to carbon prices and decreasing capacity factors.

Geothermal's LCOE is likely to decline modestly as technologies improve, but the pace will be limited by the uneven distribution and accessibility of high quality resources.

New electricity generation decided by economics

Average revenue-adjusted levelized cost of energy (USD/MWh)

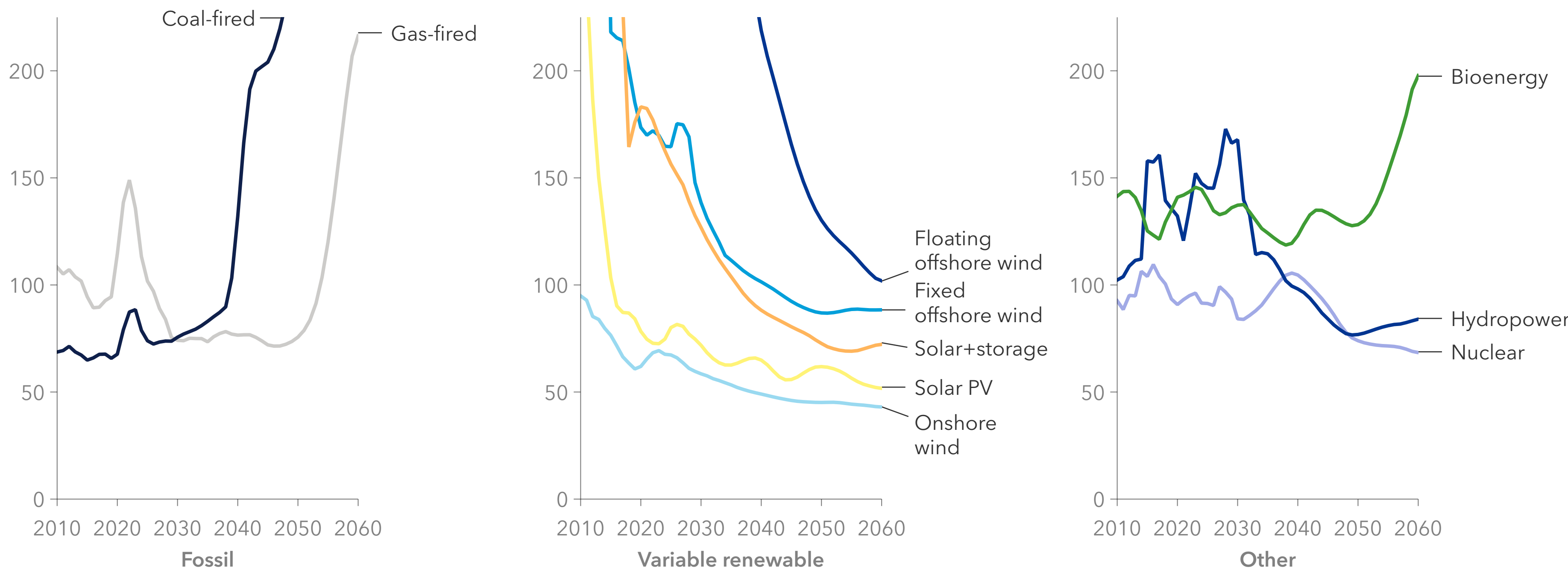


FIGURE 3.3 | Global LCOEs are weighted by regionally installed capacities and averaged over three years. Historical data source: GlobalData (2025), DNV analysis

New power system stability

High renewables penetration is not the primary cause for grid blackouts, such as the recent incident on the Iberian Peninsula, but the new energy system needs updated stabilization management and increased flexibility. While transitioning energy systems, such as those in Spain and Portugal, do have less spinning inertia which helps stabilize the grid, inverter-based variable renewables and storage can actually be more adept at managing frequency and voltage fluctuations.

A grid's frequency is stable when supply of electricity matches demand. Losing a major power supply disrupts the frequency stability. If this is not corrected, the grid can be lost. A power system with large amounts of fossil, nuclear, and/or hydropower has a lot of synchronous generators. If generation or transmission is lost, the inertia of the system resists the drop in frequency for a few seconds, providing time for other generators to react and stabilize the grid.

The current technical implementation of most solar and wind power cannot intrinsically provide grid stabilization in the case of losing a generator. However, if equipped with controllers designed to detect and respond to frequency and voltage disturbances, these systems have the potential to react much faster than traditional rotating machines. Battery storage provides temporal flexibility and can be used by grid management to store power when there is a drop in demand and provide power when there is a drop in supply.

The grid needs both hardware and software upgrades during the transition. This requires significant investment, particularly during intense periods of renewable build out. Spain has had one of the lowest ratios of grid to renewables investment in Europe, 30% compared to a European average of 70% (EnergyMix, 2025).

Interconnectors with neighbouring countries also help, reducing the contribution of any one generator. Spain only has 3 GW of interconnection capacity, one-fifth of the EU 2030 target. This is partly because France has so far been reluctant to expose its nuclear fleet to cheap Spanish solar power (EnergyMix, 2025).

Electrifying power consumption also changes how grids are managed. Distributed solar, storage, EVs, and smart appliances can be aggregated into 'virtual power plants' and serve a role in managing demand to maintain grid stability. If rooftop solar systems are 'islanded' they can continue to generate electricity without a grid connection.

Traditionally, a synchronous generator has been needed to restore power during a 'black start' after a partial or total loss of electricity. This can be provided by hydropower, nuclear, or geothermal generators in a fossil-free system. Currently, wind and solar farms cannot perform a black start and only come back online after a skeleton transmission system is restored. However, some new turbines come equipped with functionalities needed for grid restoration, and the European organization of transmission system operators (ENTSO-E) has included black start capabilities as an optional requirement for new wind farms (ENTSO-E, 2013).

Data centre and AI energy demand

As we observed in Section 2.4, the present exponential growth in investments and deployment of AI is likely to give way to a more linear – but still very steep – growth in AI services in the next few years. That AI is perceived to be pivotal to economic power and geopolitical influence (Gewirtz, 2025; Economist, 2025b) is not in question, nor is the fact that it is likely to have a profound, economy-wide impact over time. What concerns us as energy forecasters, however, are the implications AI has for energy demand and use.

AI model training and use takes place in large data centres, which have grown exponentially in both number and size, with global investment doubling since 2022 (IEA, 2025). The installed capacities of data centres range from a few megawatts to over one gigawatt, requiring similar amounts of energy to that produced by a large-scale nuclear or coal-fired power plant.

Different types of data centres

There are several types of data centres catering to different needs. In our model, we group them into **general purpose data centres** and **AI data centres**. General purpose data centres handle traditional workloads like email storage, data backup, high-frequency trading, real-time communication, gaming, streaming, and crypto mining. AI data centres include both those used to train AI models and those used for inference – where a trained model takes new data to make decisions or predictions.

To determine the overall market size and related energy demand for general purpose data centres, we look to the rate and depth of digital diffusion in each of our world regions, which broadly correlates with increases in GDP per capita.

We have implemented a separate dynamic to drive the market demand for AI services. Our hypothesis is that demand is driven by AI's capacity to perform cognitive tasks, and therefore augment and replace human labour (Epoch.AI, 2025). Compensation paid to human labour makes up about half of GDP (Our World in Data, 2025). If AI – combined with embodied AI – augments, automates and replaces a certain percentage of that work, its value will increase with the share of the economy it replaces.

So, the driver for AI training is to increase the number of cognitive tasks that can be performed by AI, which through inference can be converted into services available for consumers and companies to utilize and automate tasks.

There are then two offsetting trends: rising demand for digital services versus improving efficiency, which leads to lower energy demand per unit of the compute needed to provide the AI service. The net of these determines energy growth, and the overall cost of training compute.

Efficiency gains

Computation per unit of energy (FLOP/s per Watt), has improved, doubling every three years (Epoch.ai, 2025). We expect this trend to continue with improvements in chip design and smaller node size until reaching the 1 nm scale. We also expect further efficiencies in the form of better architecture, algorithms, and cooling engineering at data centres – the combined effect of which will be multiplicative. There is a feedback loop at work, however: as energy costs per computation fall, that in turn encourages greater investment in training, leading to more powerful AI, new and extended use cases, rising demand, and so on.

Estimating AI's energy appetite

Energy demand from AI and data centres grows rapidly towards 2030, with North America leading and consuming half of all energy used by AI and data centres by then. From 2035, energy demand from AI training and inference will surpass all other data centre use. By 2060, 80% of data centre energy demand will come from AI, and total energy from the sector will represent 11% (6,400 TWh) of final electricity demand, slightly less than global space cooling electricity demand and slightly more than Europe's electricity demand.

In the near term, the balance between rising demand and physical constraints will determine how quickly capacity can be added. The appetite for new digital

AI electricity demand will grow ten-fold to 2030

Data centre energy demand (TWh/yr)

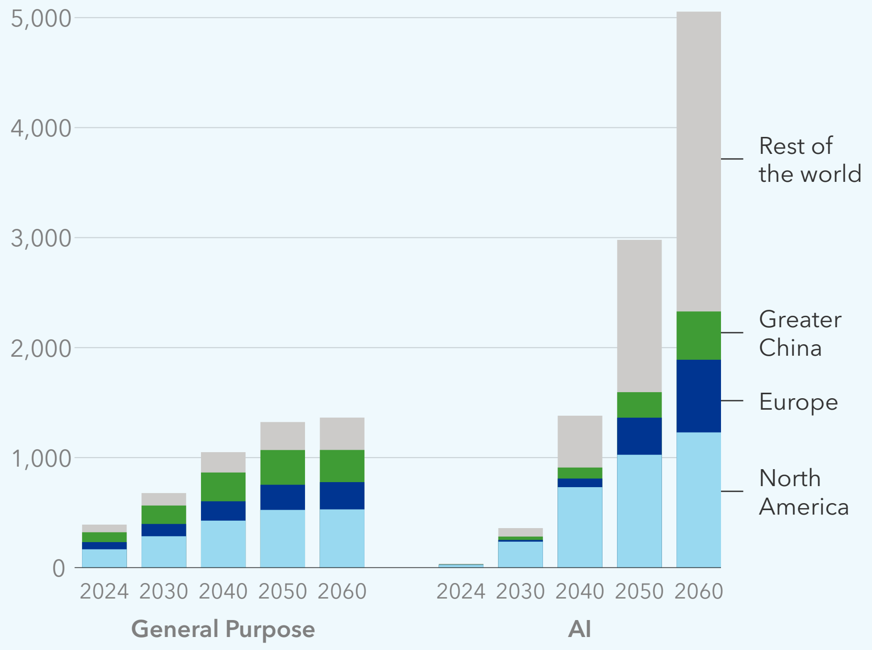


FIGURE 3.4 |

and AI services is strong, but expansion depends on two bottlenecks: semiconductors and electricity grids. If either lag behind demand, deployment slows and costs remain high; if both expand in step, construction accelerates, and services spread more quickly. Thus, if underlying demand could support annual additions of 40–50 GW of new capacity in the early 2030s, actual growth will track the pace at which chips and power connections become available. The sector therefore scales at the rate set by its supply chains – and the willingness of investors to finance physical infrastructure under conditions of scarcity – rather than by unconstrained demand.

Beyond 2030

Looking further ahead, the dynamics are increasingly shaped by technology scaling and cost. Each shift in process node – from mainstream 14–22 nm designs to advanced 5–10 nm, and ultimately to leading edge nodes at 3 nm and below – raises computational output per chip by close to an order of magnitude, while power per calculation falls by roughly a factor of two to three (Epoch.ai, 2025). These efficiency gains bring down the cost of compute and allow training runs to expand. Average computation requirements for AI models collectively rise from around 10^{20} FLOPs in the 2020s to above 10^{30} FLOPs by mid-century, still below the levels often cited for general AI. Manufacturing learning curves add further reductions: each doubling of cumulative chip production lowers cost per unit, reinforcing uptake. Efficiency lowers energy use per calculation, but because it also makes computation cheaper, it stimulates more demand.

Electricity supply adds another dimension to this transition. In the past, the economics of capital-intensive facilities favoured continuous operation and reliable baseload supply from the grid – typically supported by gas-fired generation. Grid access was therefore essential, and developers sought large, stable connections to maximize utilization. That logic is changing. Grid congestion, rising carbon constraints, and the falling cost of renewables incentivize different operating models. Smaller, modular data centre facilities can be deployed closer to where power is available, scaled up over time, and run flexibly to avoid peak load periods or follow variable generation. This shift opens the possibility that part of future data centre growth could integrate more closely with renewables rather than relying exclusively on large grid connections. Flexible data centres capable of shaping their demand profile may evolve from a niche to a mainstream option, aligning economics with the wider push for lower-carbon grids (Lovins 2025).

Uncertainty

The growth of AI is highly uncertain, and our results reflects the structure of our model and the assumptions we have made. Improvements in chip technology, algorithms, and the economic benefits of AI all contribute to the rate of progress. We made assessments based on historical trends and expert opinions on future developments, which are especially uncertain for data centres. Energy demand follows the growth in AI use, but there are limits to how fast AI can scale, which we have tried to implement. The amount of available energy, grid expansion, chip production capacity, and availability of training data all contribute. Further in the future, issues like chip node size, latency, and bandwidth could be limiting factors. At the same time, new chip designs like neuromorphic chips could change the calculation efficiencies and create a new paradigm for AI.

DNV on low side of data centre energy demand estimates
Global AI and data centre use in 2030 (TWh)

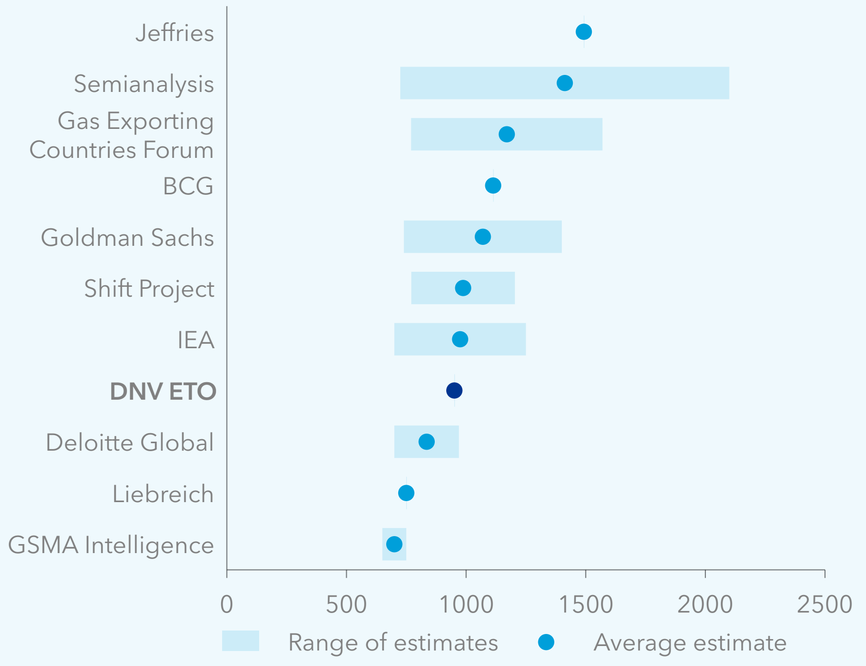


FIGURE 3.5 | Sources are from 2024 and 2025.

A review of over 50 publications with recent estimates (Kamia and Coroamă, 2025), shows a vast range in global data centre energy demand for 2030 (210-7,900 TWh) (Figure 3.5). Our forecast lies on the lower end of the base case estimates. Towards 2040 and beyond, there are limited sources to compare with and likely much higher uncertainties. Our forecast necessarily reflects assumptions based on existing technology developments, the persistence of which is itself highly uncertain. For example, we assume that AI will not be wholly immune to the productivity paradox that has characterized information technology investments to date – famously summarized in Robert Solow's quip that, "You can see the computer age everywhere but in the productivity statistics" (Solow, 1987).

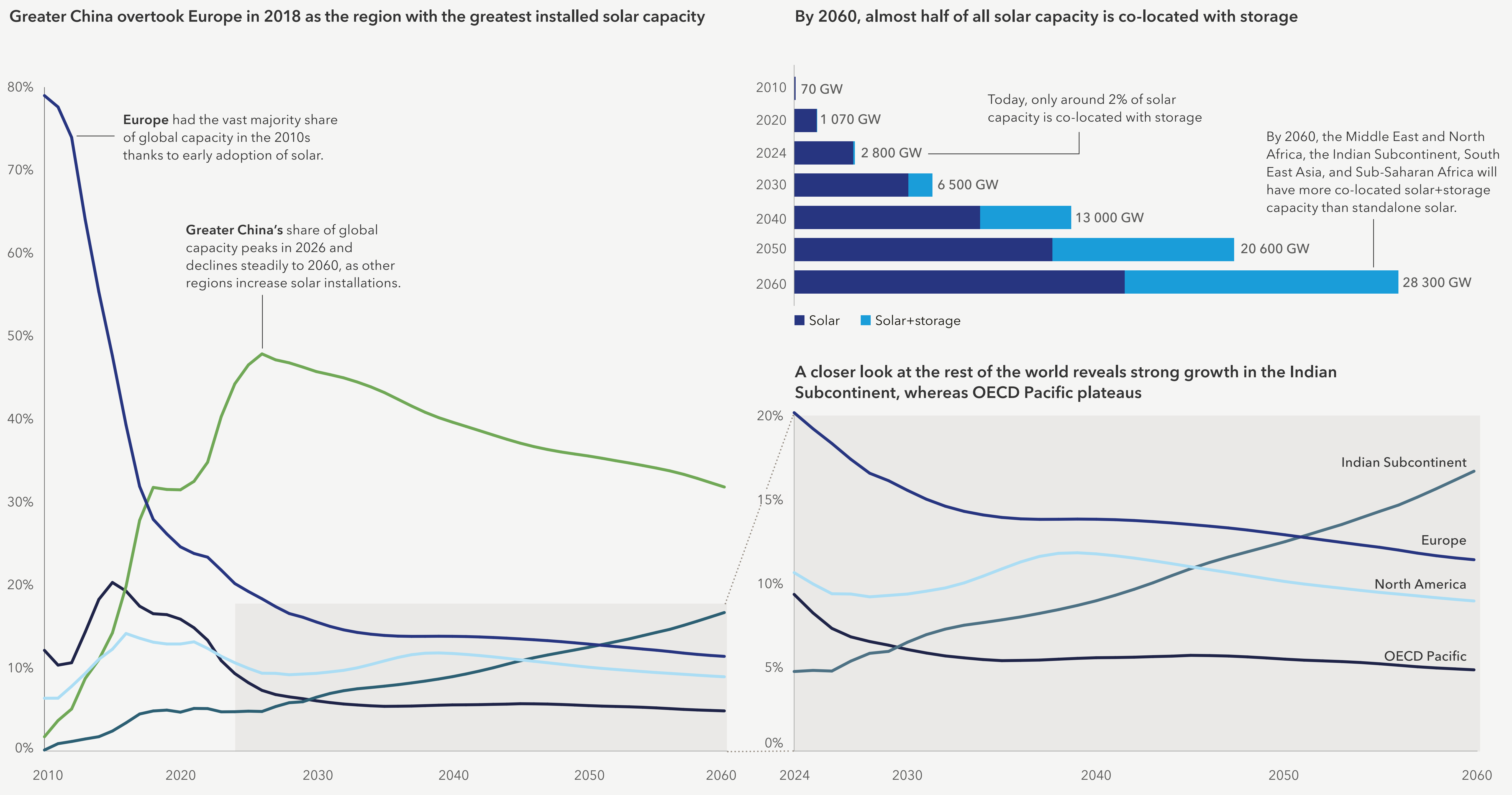
We are also sympathetic to the view advanced by the OECD in micro-to-macro modelling of AI's contribution to labour-productivity which suggests that aggregate gains from real-world AI deployment will likely align with mainstream productivity ranges rather than with a step-changes. Yet, how that unfolds over time is uncertain because technological breakthroughs will inevitably occur (e.g. AI evolving to learn from the real world and not static data sets).

3.2 SOLAR

Solar is definitively the most dominant renewable and is on track to become the most significant energy resource

- In 2060, solar power will account for 47% of electricity generation, increasing five-fold from 2024. Already in June 2025, solar was the biggest supplier of electricity in the EU (Ember, 2025).
- Solar's meteoric rise has been driven by falling costs of modules as production moved to China. The LCOE is now sufficiently low to maintain the rate of installations, which are set to plateau overall, but continue increasing in the Global South.
- From the mid-2030s onwards, around half of new installations will be co-located with storage, up from 6.6% today, and around half will be distributed generation, up from 33% today.
- Battery packs can shift power production time two to four hours into periods with higher demand, reducing the cannibalization of electricity prices that are already seen in the European market.

Solar co-located with storage gains prominence to shift hours of energy generation



Total capacity in GW_AC. The other five world regions have less than 10% share of global capacity each and are not shown.

Growth in distributed solar set to outpace utility installations in some key regions

Now a mature renewable technology, solar power is undergoing two major shifts: it is increasingly co-located with battery storage and generation is increasingly distributed to households and businesses.

Solar power's production peaks at midday while electricity demand is highest in the evening. In regions where the market sets the price of electricity, solar power has the lowest average revenue.

Distributed generation's growing share

Global installed capacity (GW)

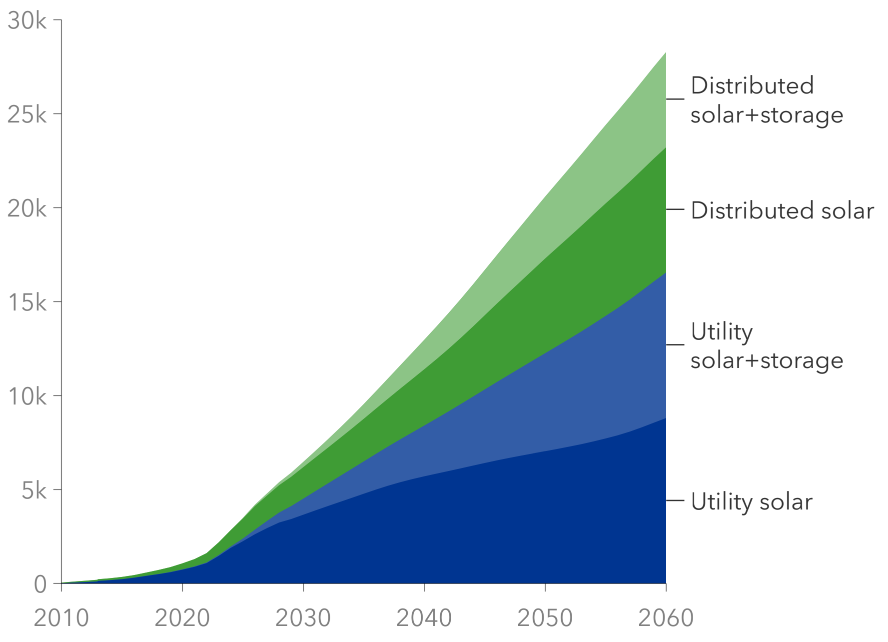


FIGURE 3.6 | Historical data source: GlobalData (2025), IRENA (2025)

By co-locating storage with solar plants, producers can instead charge batteries during peak solar production and discharge to the grid when electricity prices are higher. This, coupled with the falling costs of lithium battery packs, leads to a projected ten-fold increase of co-located solar and storage capacity (both utility and distributed) from 2024 to 2029 and a 100-fold increase to 2049. By the mid-2030s, the difference in average received energy price between co-located and standalone will be significant enough that the annual revenue of a co-located utility plant will be around 15% higher than a standalone plant, despite an OPEX twice as high and a lower capacity factor.

Distributed generation includes behind-the-meter (BTM) residential and commercial solar and off-grid solar. BTM's popularity is growing as a way of reducing electricity bills in developed regions, and as a buffer from unreliable electricity grids in developing regions (see Behind-the-meter on page 50). Off-grid solar systems provide access to affordable electricity to millions of people, up to 10% of the population by 2060, who would otherwise rely on diesel generators or traditional biomass for light.

In 2024, distributed systems accounted for 31% of global solar capacity, of which 24% are off-grid and 7% are BTM. Installed BTM capacity will increase compared to off-grid, but will remain under half of total distributed throughout the forecast period. The proportion of distributed systems will trend slowly upwards over the coming decades, plateauing at 40% from 2050.

Net distributed additions overtake net utility additions by the 2040s in all regions except North Eastern Eurasia and the Indian Subcontinent. This is despite several countries that have experienced high distributed solar uptake in the past decade reducing generous supportive policies, such as China (Shaw, 2025), Australia (Energy Australia, 2025), and the UK (Abeni, 2025). Most notably, China's government changed grid access rules for projects built after May 2025, resulting in 36 GW of new rooftop solar in Q1 of 2025 (Rystad, 2025).

In most countries, distributed solar is now driven by the ability to save on high electricity prices and the falling costs of solar and battery modules, rather than relying on support policies such as feed-in tariffs.

In Europe, Latin America, Greater China, and the OECD Pacific we expect a drop in utility solar installations, including co-located, during the early 2030s compared to the 2020s. This drop will be highest in the OECD Pacific at 44%, and lowest in Greater China at 3%. Europe and Latin America will drop 28% and 25% respectively.

The drop in installations will be due to constricted grids, price cannibalization, and the marginally lower revenue-adjusted LCOE of onshore wind.

Distributed generation reaches parity with or outpaces utility installations in most regions

Net capacity additions in select regions by decade (GW_{AC}/yr)

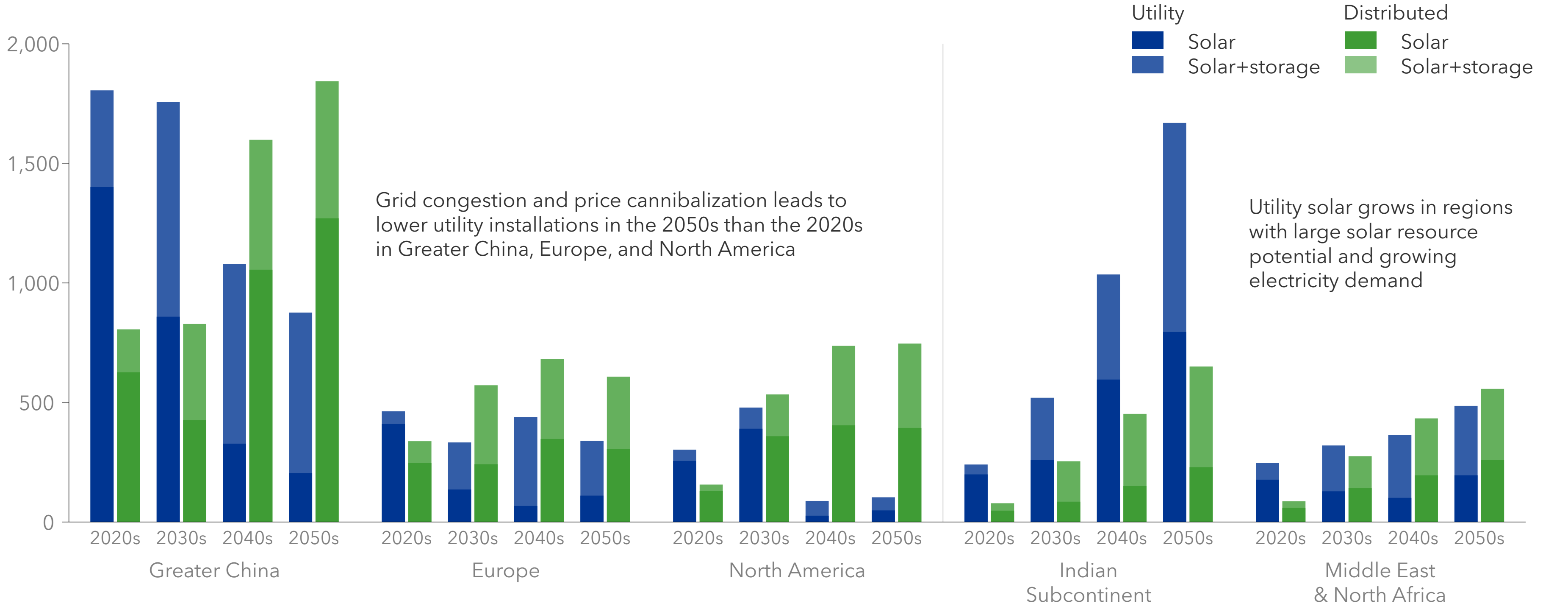


FIGURE 3.7 | Historical data source: GlobalData (2025)

LCOE stabilizes as module prices begin to plateau

Solar power is the least expensive new power capacity to build in most regions and only slightly more expensive than onshore wind in Europe and Sub-Saharan Africa. It is also the quickest to build, with most utility power plants able to come online within a year of the final investment decision (FID), half that of onshore wind. This is particularly relevant in regions with rapidly rising electricity demand in the near term, such as Greater China and Europe.

We expect the global LCOE for solar to stabilize after a decade of rapid decline. Compared to an average annual drop of 8% over the last ten years, this will be approximately 5% for the rest of this decade, 3% in the 2030s, and under 1% in the 2050s.

The halving of solar's LCOE in the past ten years has been a result of module production shifting from Europe and the US to China, which now produces 80% of solar modules. In 2023, China invested USD 130bn in new manufacturing capacity and supporting loss-making producers – mostly state-owned enterprises and companies affiliated with the Chinese government (Wood Mackenzie, 2023).

As a result, China's production capacity was double global installations in 2023, and panel prices fell 42% (Hayley, 2024). The low prices have caused some manufacturers both within and outside China to exit the market. In 2024, the Chinese industry ministry published new investment guidelines aimed at curbing overcapacity and stabilizing module prices (Howe, 2024). There have been indications that production is declining and prices are dropping more slowly since the policy change (Xiao, 2025).

As a result of these shifts, modules – which were once the largest contributor to solar costs – now account for just 18% of a CAPEX for a globally averaged utility plant. The majority (74%) is a balance of system, including labour for installation, and other equipment such as racking and inverters. The remaining 7% is grid costs. Future cost reductions will come from installation efficiencies and learning curves in other components such as inverters.

Grid costs are shared by the developer and the grid operator to varying extents in different jurisdictions. Our model shows increasing grid costs which will have correspondingly varying effects on project costs around the world. On a global average, grid costs will be a larger part of a project budget than modules from the late 2040s.

The modest reduction in the CAPEX of co-located solar+storage plants is attributable to savings in balance of system costs and not falling battery module prices. This is because the hours of storage of a typical battery are increasing, and more battery capacity is being installed on co-located plants. As a result, while the cost per MWh of battery is falling, the cost per MW of solar remains relatively constant.

Solar and solar+storage CAPEX stabilizing
CAPEX components (USD/MW)

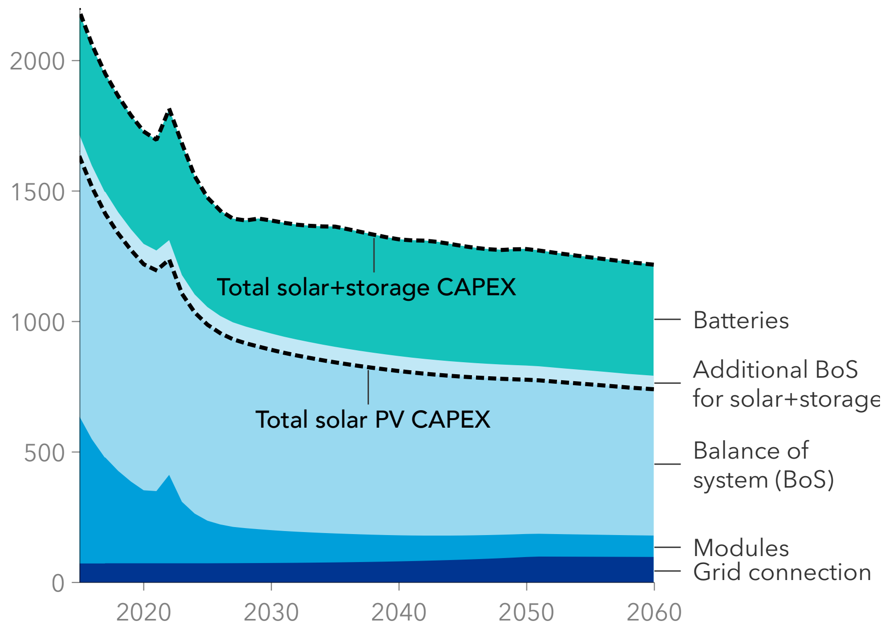


FIGURE 3.8 | Battery prices are reducing quickly, so more battery capacity is installed per MW of solar, leading to stabilization of battery CAPEX.

Solar LCOE most affected when adjusting by revenue
Global average levelized cost of solar energy (USD/MWh)

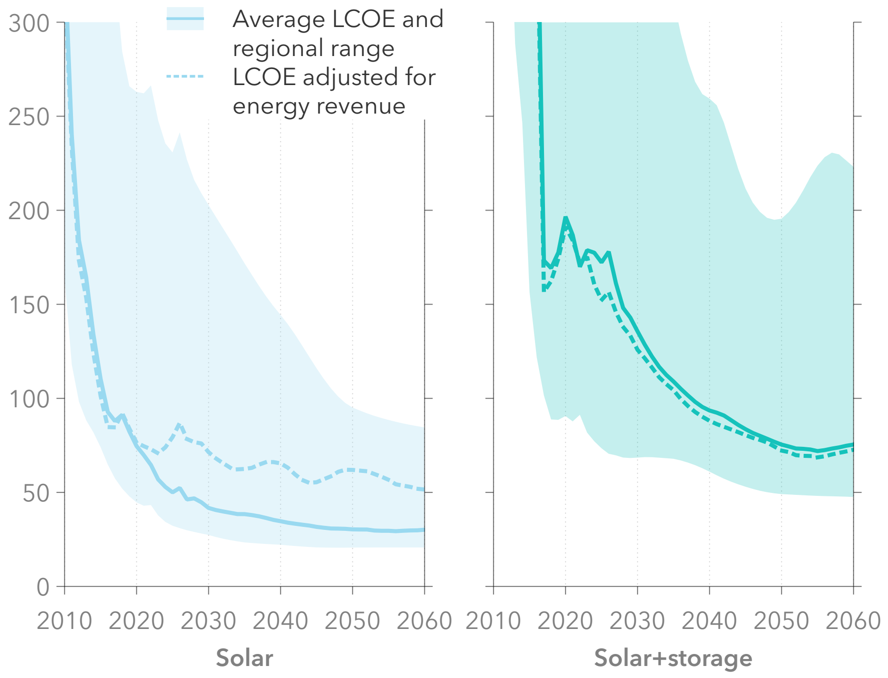


FIGURE 3.9 | Historical data source: GlobalData (2025)

Solar received price dropping below wholesale price
Capture price (USD/MWh)

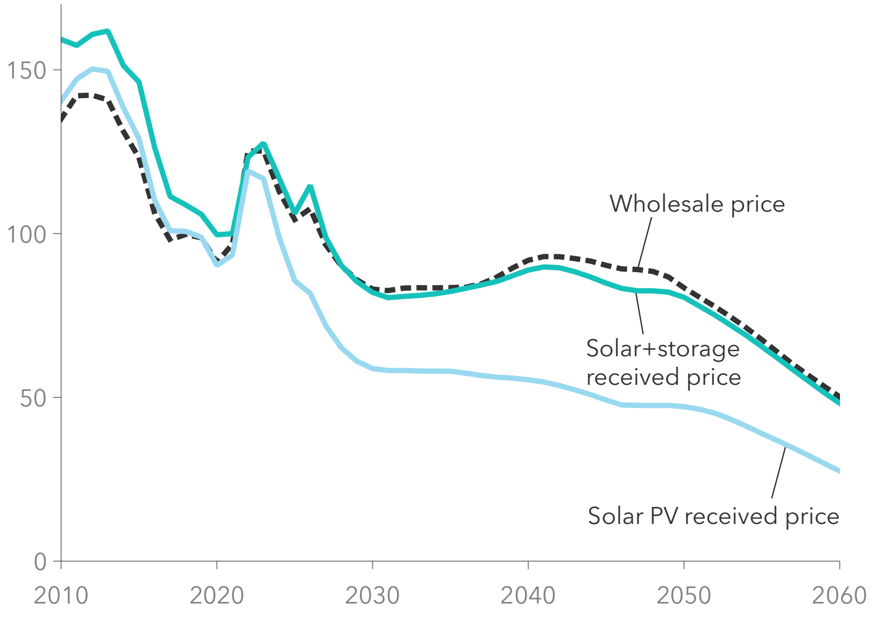


FIGURE 3.10 | Historical data source: IEA (2025), EIA (2025), Eurostat (2025)

Behind-the-meter

BTM distributed solar generation, both with and without storage, is poised to play a significant role in addressing buildings' energy demand in the future. Distributed solar generation, self-consumed, supplied 2% of the total building electricity demand in 2024. We forecast this will increase to 10% by 2060, and 13% of total electricity demand will be met with BTM, both self-consumed and fed to the grid. Furthermore, 30% of solar electricity will be generated by distributed solar connected to the grid.

BTM solar refers to distributed solar generation installed at residential or commercial buildings, primarily for self-consumption, with feeding electricity into the grid a secondary concern. This model, also known as solar prosumerism, differs from utility-scale solar in several ways:

- Capital and fixed costs are typically higher per unit of capacity due to smaller scale and self-financing.
- System size ranges from 1 kW to 100 kW, compared with MW- or GW-scale utility projects.
- Motivation is centred on reducing on-site electricity consumption, while utility-scale solar is designed for wholesale grid supply.

In 2024, the vast majority of distributed BTM capacity consisted of solar-only installations. This dynamic is beginning to change as more regions roll out smart-meter infrastructure and implement time-of-use tariffs across both residential and commercial segments. These policy and technology shifts are catalysing broader adoption of solar+storage systems. At the same time, rising solar penetration on the grid is pushing midday wholesale prices down, often close to zero, which reduces the value of exporting excess generation. Under these conditions, pairing solar with battery storage allows households and businesses to capture surplus solar production, avoid curtailment, and shift consumption to periods when grid electricity prices are higher. This capability strengthens the economic case for storage while also enhancing system flexibility and resilience. By 2050, we forecast more distributed solar+storage systems than solar-only systems globally.

Adoption dynamics are different

BTM solar adoption is shaped by two main dynamics: cost/incentive-based and need-based.

Cost- and incentive-driven adoption
In many developed countries, households and businesses adopt BTM solar to reduce electricity bills. Supportive policies such as feed-in tariffs, net metering, and capital subsidies have historically encouraged this trend, with clear examples in countries like Australia, Germany, and Spain (Collings, 2025).

However, in these regions, high solar penetration and the introduction of time-of-use tariffs have made stand-alone solar less profitable. Focus is shifting instead to solar-+storage systems, where prosumers store excess energy and use it during peak-price periods to maximize savings. This is also supported by growing adoption of dynamic feed-in rates, declining lithium-ion battery costs, and evolving grid tariffs, taxes, and levies.

Need-based adoption
In other contexts, BTM solar adoption is driven by energy reliability concerns. Households and businesses in regions with unstable grids – such as India, Pakistan, and South Africa – turn to BTM solar (often with storage) to maintain power during outages (Yeshwanth, Mumtaz, and Saha, 2024). Here, solar is valued less for cost savings and more for its role in resilience and energy security. In these markets, solar systems are increasingly replacing diesel generators as a cleaner, quieter, more sustainable backup solution.

As solar and storage prices continue to fall, we expect resilience-driven adoption to grow in both weak-grid regions and urban areas seeking energy autonomy. However, need-based adoption is constrained by the households and businesses that can afford the upfront cost of purchasing and installing systems, and the rate at which grid access improves.

The grid's ability to reliably meet electricity demand also affects the role and magnitude of distributed solar. In the Indian Subcontinent, while the absolute

Distributed solar+storage is expected to overtake solar-only capacity globally in the 2040s

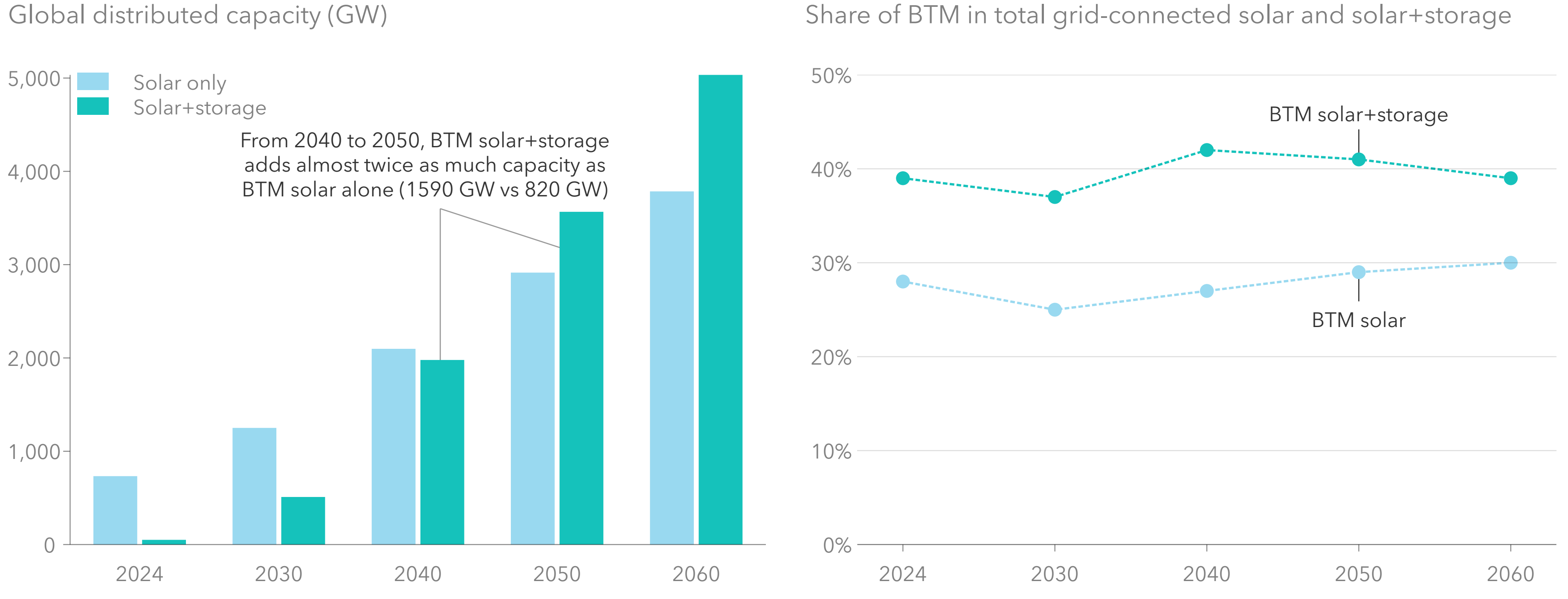


FIGURE 3.11 | Increased solar+storage adoption is driven by reduced cost of batteries.

amount of BTM solar installed is expected to grow year over year, its growth rate remains slower than that of utility-scale solar. This is largely because rising electricity demand in the region will be met by the grid, with continued improvements in grid infrastructure and access reducing the urgency or necessity for distributed solutions.

Recently, the surge in data centre and AI-driven electricity demand has made BTM solar and storage in commercial buildings a cost-effective interim solution while awaiting grid connections and utility capacity upgrades. This approach aligns with the 'all-of-the-above' strategy adopted by many hyper-scale data centres in North America.

While regions can be broadly characterized by either cost/incentive-driven or need-based adoption of BTM systems, it is important to note that all regions exhibit a mix of both dynamics. Moreover, the motivations for adoption are evolving over time, influenced by changing markets, policy, and grid conditions. Figure 3.13 shows the average LCOE for three typical solutions. Even in regions where cost- and incentive-driven adoption of solar and solar and storage systems dominates, there will be households or businesses for whom solar prosumerism is not yet financially viable. Conversely, in need-based regions, reaching cost parity for solar or solar+storage prosumers may still lie further in the future on average, despite growing adoption driven by reliability concerns.

Adoption of BTM systems does come with concerns of grid collapse (Jilani, 2025). This refers to the strain placed on electricity grids when a high share of consumers generate their own power, reducing their reliance on the grid. This can lead to: reduced utility revenues, making it harder to maintain infrastructure; voltage instability and reverse power flows, as excess solar is pushed back into the grid; and load shifting issues, where grid demand drops midday but spikes sharply in the evening (the "duck curve").

However, making correct policy choices with respect to rate design (time of use versus differentiated pricing for power demand) and investments into grid upgrades and storage can mitigate grid collapse while reaping the benefits of resilience and localized energy security that BTM systems can provide for a region.

While solar remains by far the most widely adopted form of distributed energy across the globe, there are isolated instances of other renewable technologies being deployed, particularly at the community level. However, these alternatives, such as BTM wind (Byrne, MacArtain, and Reaburn, 2025), remain niche and are unlikely to scale meaningfully in the foreseeable future.

BTM solar PV and solar+storage adoption trends will vary across regions, but will continue to be substantial

Capacity additions by region (GW/yr)

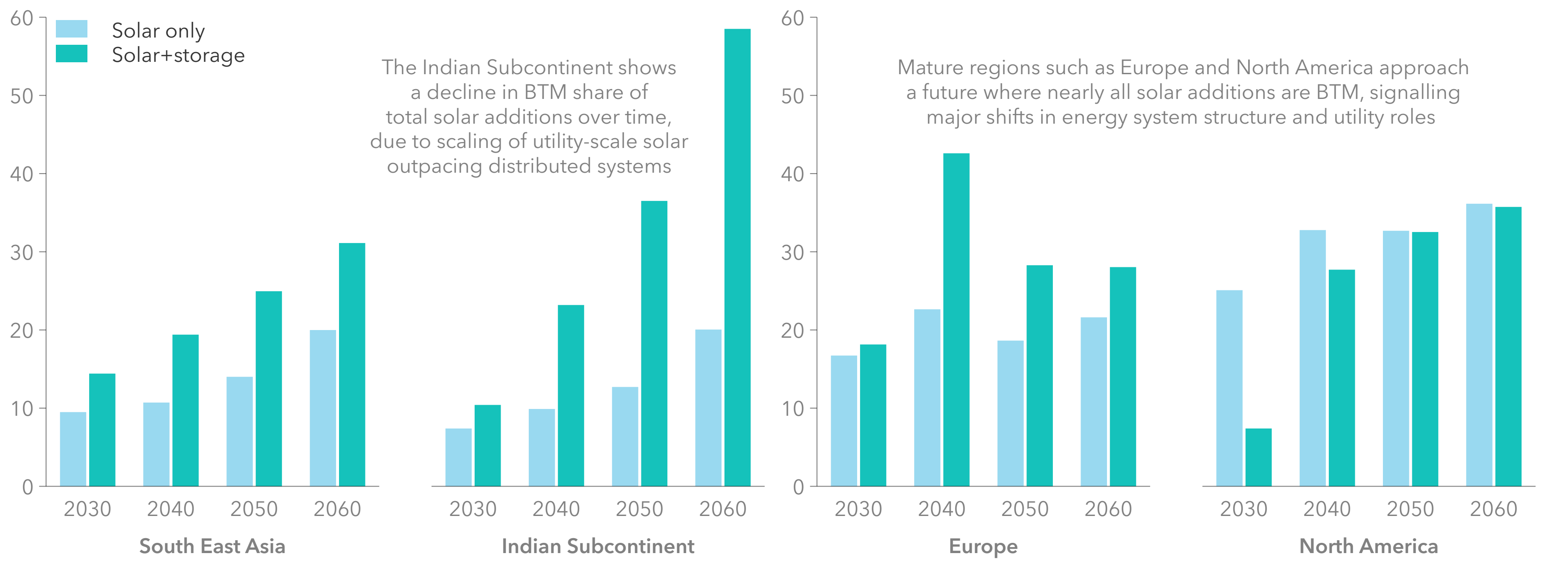


FIGURE 3.12 | The Indian Subcontinent and South East Asia see needs-based adoption, Europe and North America see cost- and incentive-based adoption.

Solar BTM prosumerism is becoming cheaper than being a pure grid residential customer in many regions

Levelized cost of electricity of prosumer options (USD/MWh)

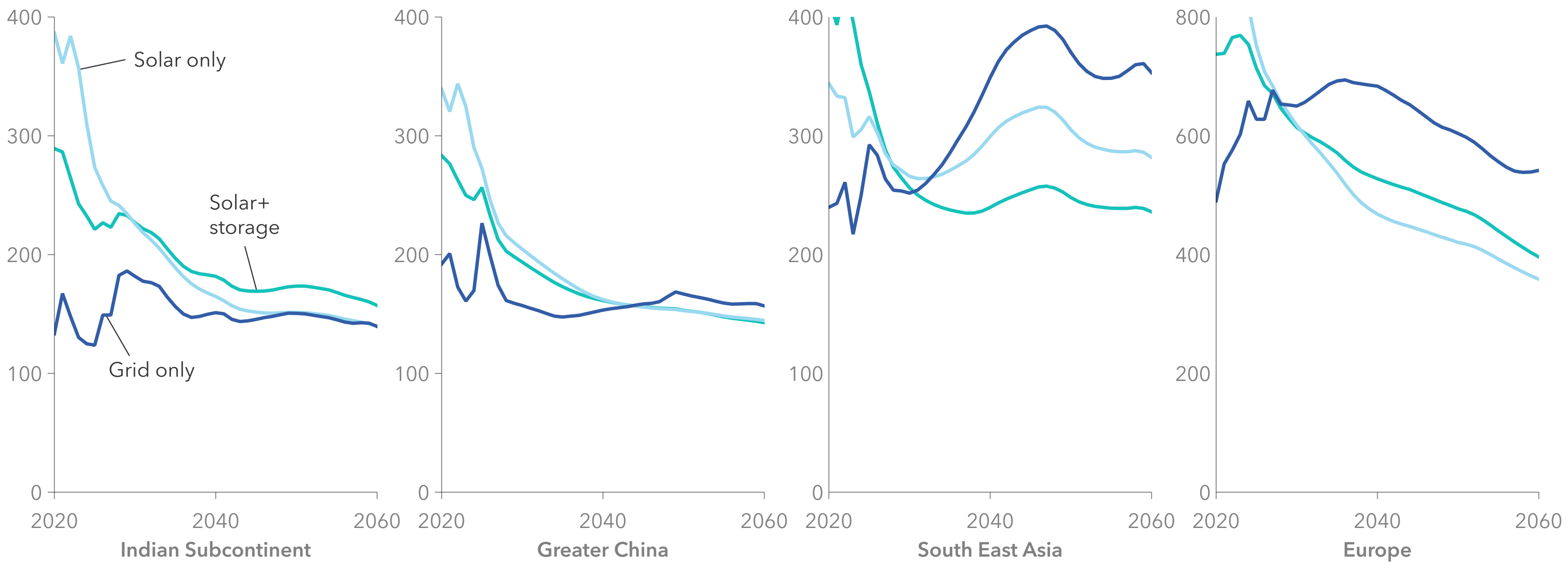
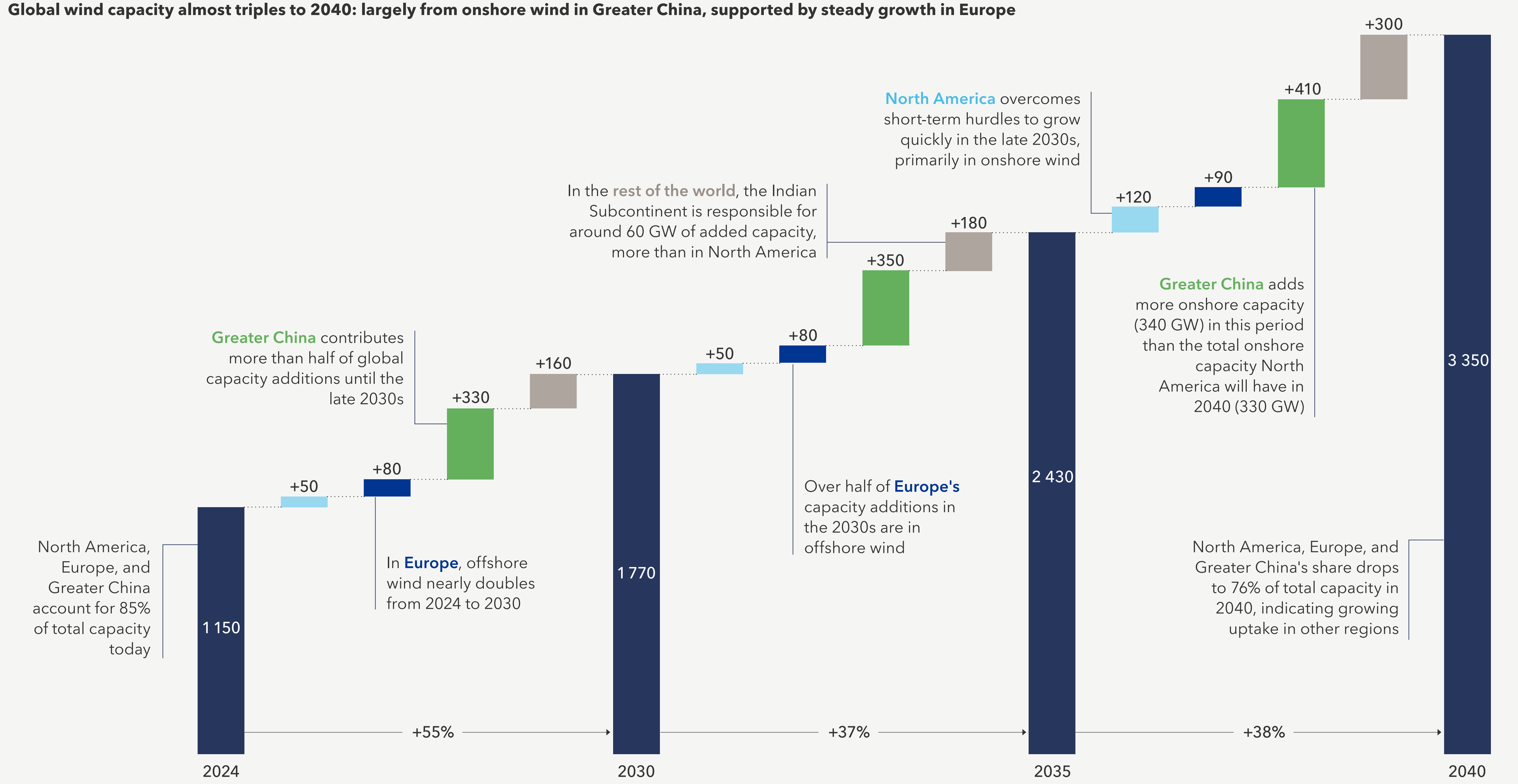


FIGURE 3.13 | The Indian Subcontinent exemplifies need-based adoption whilst Europe exemplifies cost- and incentive-driven adoption.

3.3 WIND

- Despite disrupted supply chains causing project delays in the short term, global wind capacity additions remain strong: 100 GW/yr in 2030 rising to almost 250 GW/yr in 2040 and holding steady at about 400 GW/yr from 2050.
- Regional disparities persist in future wind capacity growth. Greater China continues to dominate in total wind capacity, primarily with onshore installations, whilst Europe is the key player in offshore wind. We expect wind uptake to grow quickly in the Indian Subcontinent in the 2030s.
- Our offshore wind capacity forecast is 12% lower in 2030 than our estimate last year. This reflects continued cost inflations as well as bans and freezes of offshore wind projects in North America which slow global technology learning rates and increase the levelized cost of fixed offshore wind. These setbacks also worsen existing challenges for floating offshore wind such as lack of standardization and slow permitting.

Global wind capacity almost triples to 2040: largely from onshore wind in Greater China, supported by steady growth in Europe



	2024	2030	2035	2040
Onshore wind	1 060 GW	1 580 GW	2 050 GW	2 780 GW
Fixed offshore wind	90 GW	185 GW	360 GW	350 GW
Floating offshore wind	<1 GW	<5 GW	20 GW	40 GW

Wind is key to the energy transition

Wind, alongside solar, is pivotal for the energy transition. Wind uptake remains strong due to substantial cost reductions over the past decades, despite grid bottlenecks, global supply chain disruptions, slow permitting, political flipflopping, and community opposition. Total global wind power capacity will more than triple from 1 TW today to 3.3 TW in 2040 and will triple again to 9.9 TW in 2060. Today, the share of wind in global electricity generation is 8%, over 90% of which comes from onshore wind. In 2060, wind will account for 32% of global electricity generation, the second largest share of any energy source.

Regional differences for wind to 2040 and beyond

Wind's share of electricity generation varies greatly between regions: from less than 1% in North East Eurasia, to 17% in Europe, which has an established sector with strong technical capabilities and supportive policies. North America has the third largest wind capacity, but the sector faces uncertainty in the short and medium term due to the hostile policy position of the new US administration.

Wind will make up 27% of Europe's electricity mix in 2040, the highest regional share globally. Europe's steady onshore growth and quick offshore growth is thanks to subsidies, mature infrastructure, skilled labour, the EU ETS (which makes fossil fuel alternatives less competitive), and high wind potential (especially offshore wind in the North Sea). Uptake of offshore wind depends on policies that reduce financial risk and attract investment, such as CfDs. In April 2025, a consortium of European offshore wind stakeholders proposed a *New Offshore Wind Deal* for Europe, urging governments to auction at least 100 GW of new offshore capacity in the 2030s using CfDs to ensure revenue stability and lower project risk (WindEurope, 2025).

Greater China and OECD Pacific, two of the top three regions for offshore wind in 2030 thanks to a sizeable wind potential and suitable coastline, will triple their offshore wind capacity to 2040. Rapid growth in Greater China is bolstered by local turbine production capacity and consistent state support: the region's total fixed offshore wind capacity of over 240 GW in 2040 is more than the next three highest capacity regions combined (Europe, North America, OECD Pacific).

The Indian Subcontinent will also emerge as a significant market for wind, driven by rapidly increasing electricity demand from its growing population and the need to reduce reliance on fossil fuels to cut emissions per its nationally determined contributions. The region will add as much capacity from now to 2040 as North America (around 200 GW), primarily in onshore wind.

Demand for wind energy to 2040 will largely stem from new demand growth for electricity. While wind power has started to replace coal and gas in the power mix in some countries in Europe, we expect wind (and solar) to increasingly displace fossil fuels globally in the decades following 2040.

Looking forward to 2060, all regions will see substantial wind electricity generation in their power grid. We foresee that all regions will achieve at least one quarter share of wind in electricity generation except for North East Eurasia, which will continue to rely on its domestic gas production alongside solar growth. Five of the ten ETO regions will source around 40% of their electricity generation from wind (Figure 3.14).

Wind will make up 27% of Europe's electricity mix in 2040, the highest regional share globally.

Wind power also serves purposes beyond electricity. A dedicated portion of wind capacity is used specifically for hydrogen production by electrolysis. We forecast that less than 200 GW of onshore and around 20 GW of fixed offshore wind capacity will be dedicated to hydrogen production by 2060. This is lower than we have previously estimated, as we foresee that electrolysis projects will continue to be deprioritized in the short term in the wake of supply chain uncertainties.

Global wind share of electricity grows to 32% in 2060, but growth is uneven between regions

Share of wind in electricity generation by region

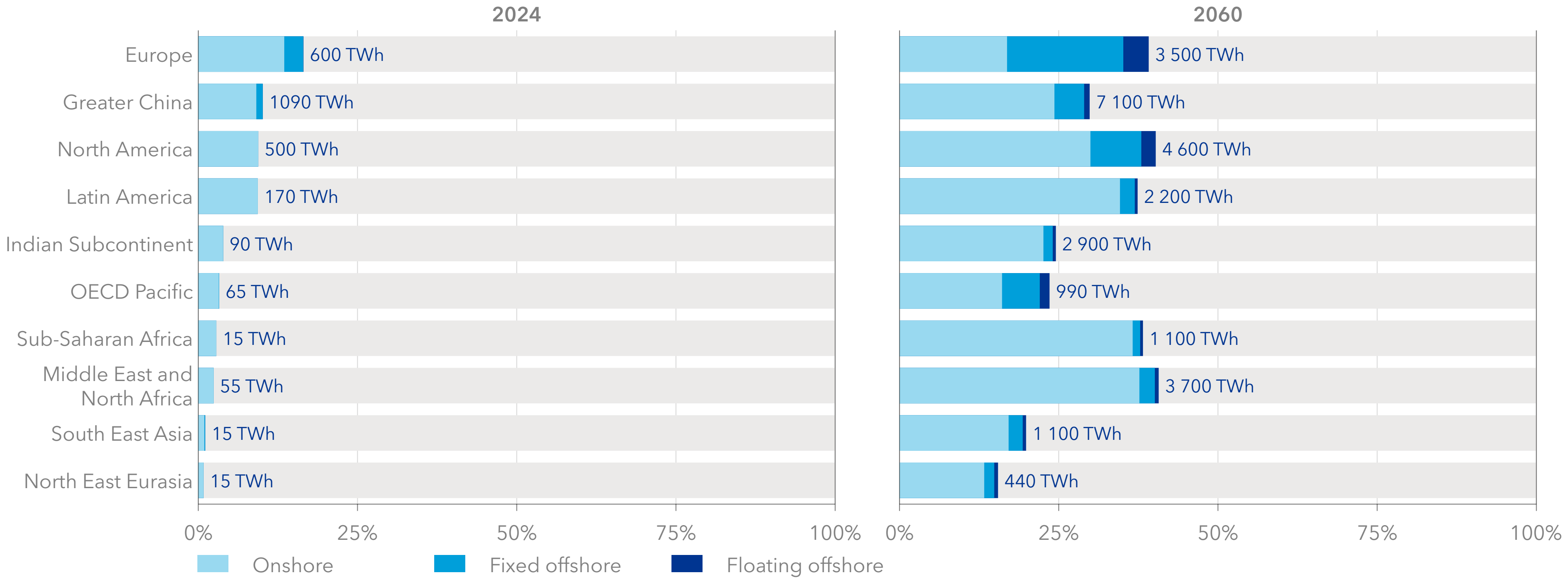


FIGURE 3.14 | Generation includes behind-the-meter and off-grid. Historical data source: IEA WEB (2025)

Levelized cost dynamics vary by component and region

The levelized cost of electricity (LCOE) of wind plays a critical role in the quantity of wind capacity coming online in different regions. There are two major factors which affect LCOE: annualized CAPEX and OPEX of wind and the total electricity generated over the lifetime of the wind power plant, which is a function of the wind conditions of the site and the turbine size.

The global average LCOE of wind will continue to fall across all three technologies to 2060 (Figure 3.15). While onshore enjoys widespread deployment due to low costs, offshore wind is increasingly experiencing delays between auction and final investment decision (FID). This trend is driven by supply chain disruptions delaying delivery of key components, fluctuations in the steel price impacting nacelle production, challenges in sourcing skilled labour necessary for installation and maintenance, and rising costs across the board.

Today, the global average LCOE for floating offshore wind (USD 390/MWh) is almost three times as much as the LCOE for fixed offshore wind (USD 140/MWh) due to the significantly greater technical and logistical challenges associated with floating installations. Floating wind also struggles with lack of standardization across its various designs, leading to fragmented learning and slower cost reduction.

Global LCOE continues to fall across all wind technologies, while Greater China has the lowest LCOE of the big three regions

Levelized cost of wind energy (USD/MWh)

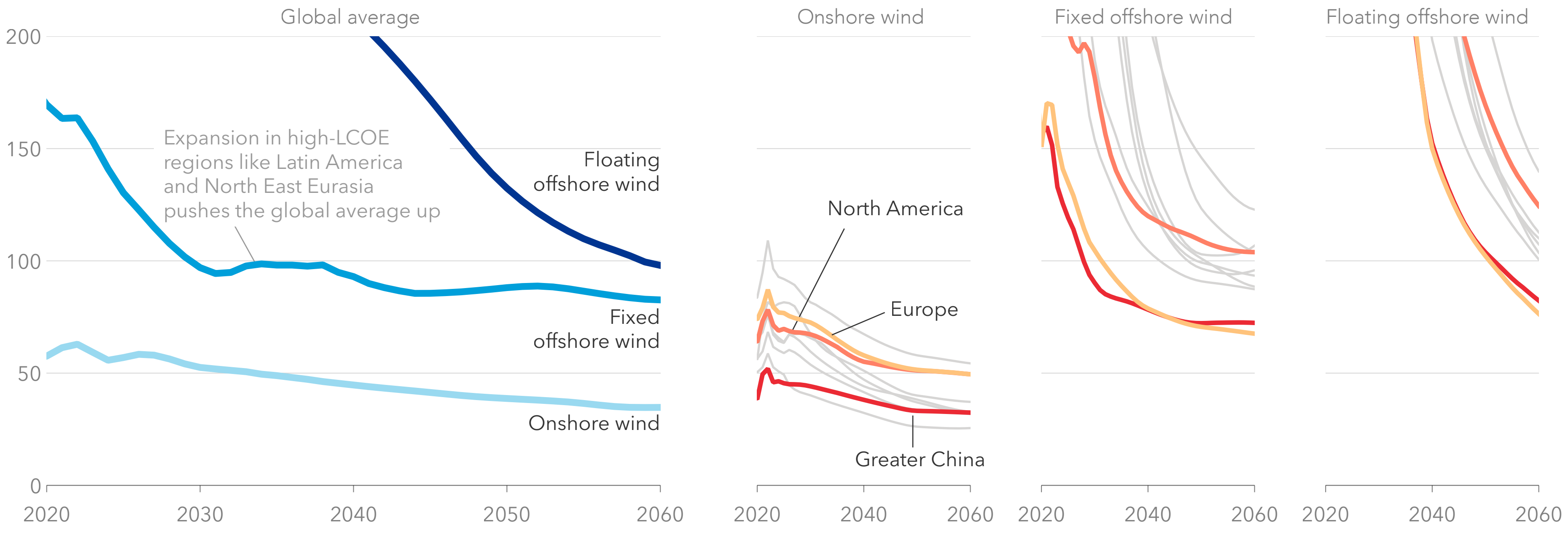


FIGURE 3.15 | Global LCOEs are running three-year averages (left). All other regions shown in grey (right). Historical data source: GlobalData (2025), DNV analysis

For the cost of floating wind to approach that of fixed, strategic policy interventions are needed that support uptake. This will lead to faster technological advancement, standardization in design and production (such as consolidating turbine size and tower designs), and economies of scale, all of which will bring down costs.

Regionally, we see that the LCOE in Greater China remains significantly lower for onshore wind than both Europe and North America. In Greater China, turbine costs are currently grossly underestimated due to extreme domestic competition and production overcapacity. This has led to artificially low turbine prices, though these are unlikely to be sustainable (Jiying, 2024; FT, 2024). Mature supply chains and low land and labour costs in Mainland China also lead to much lower LCOEs than Europe and North America.

We expect the fixed offshore wind LCOE in Europe to reach parity with Greater China in the late 2030s before continuing to fall and remaining lower to 2060, with a similar but slower trend expected in floating offshore wind. Compared to the two leading regions, we foresee the LCOE in North America will remain substantially higher for all offshore wind, as short-term adversarial policies like bans and freezes have long-lasting cost impacts.

In the 2030s, expanding fixed offshore wind in high-LCOE regions such as Latin America and North East Eurasia will push up the global average LCOE. By the 2050s, rising grid connection costs for fixed offshore projects, particularly in Greater China and the Indian Subcontinent, will offset declines in turbine and other fixed costs. Coupled with adoption in nascent, higher-LCOE markets like Sub-Saharan Africa, this will again cause a slight, temporary uptick in the global LCOE of fixed offshore wind.

Overall, fixed offshore CAPEX costs will fall in both Europe and Greater China, but grid connection costs will rise to 2060 as wind farms move farther away (Figure 3.16). Cost declines come from turbine and other fixed costs, which drop more in Europe than in Greater China where they are already low.

Fixed offshore wind grid connection cost will increase

CAPEX components (Million USD/MW)

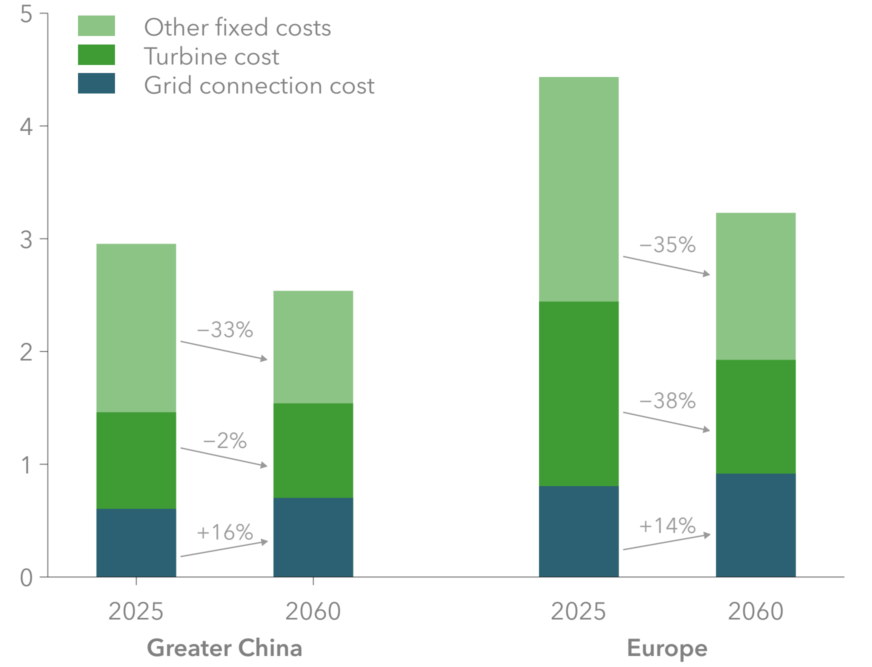


FIGURE 3.16 | Other fixed costs include e.g. construction, civil works, assembly.

3.4 NUCLEAR POWER

- Heightened attention to energy security, driven by geopolitical tensions, is reviving interest in nuclear power. Energy security shocks from the Ukraine war and broader supply chain tensions are prompting many countries to extend reactor lifetimes, re-start mothballed reactors, and green-light new builds, resulting in nuclear electricity generation growing to almost 150% above 2024 levels by 2060.

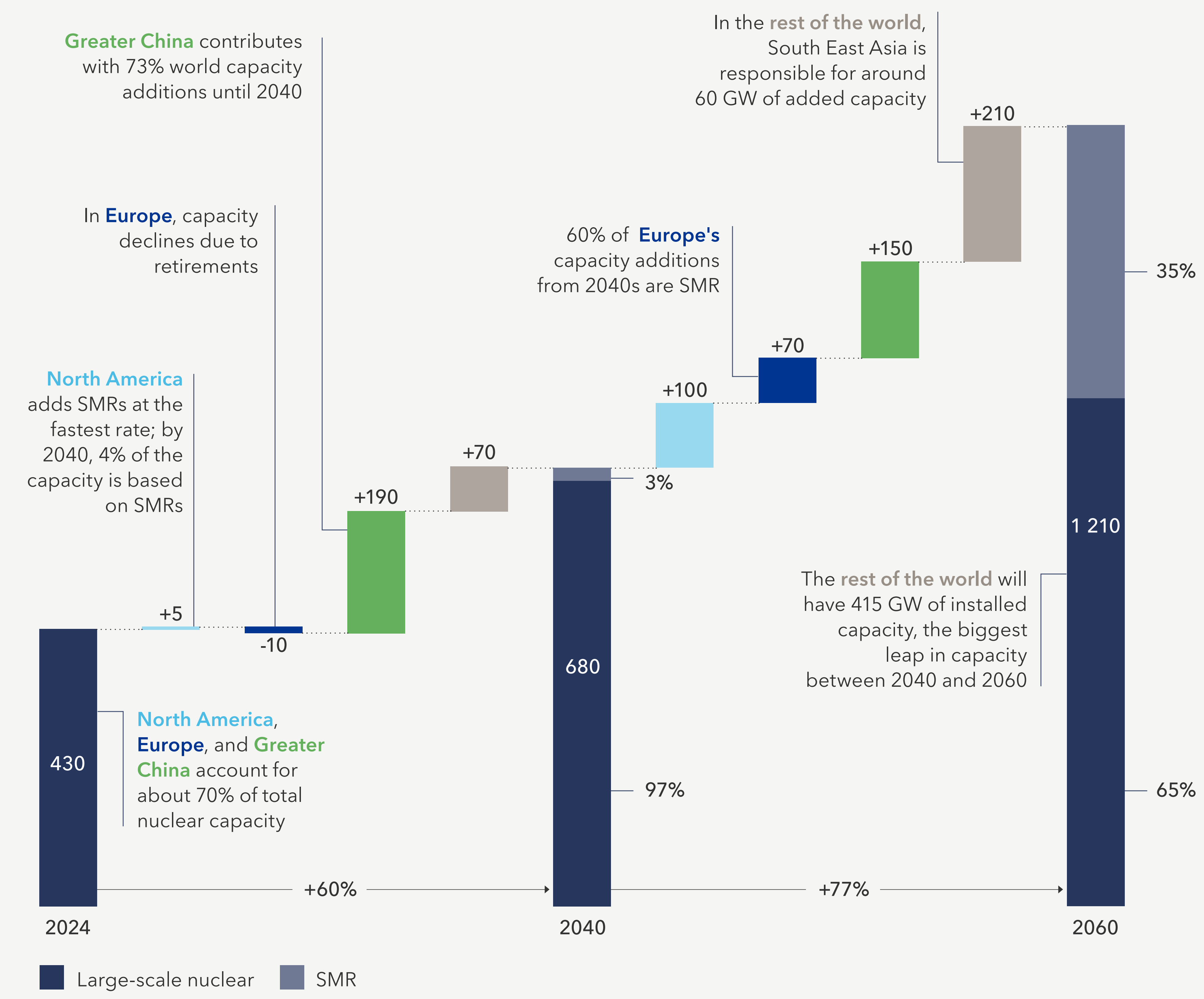
- AI-driven electricity demand strengthens the case for nuclear. Hyperscale data centres require round-the-clock, high-density, low-emission power and apparently have a high willingness to pay. This could eventually be served by small modular reactors (SMRs).

- SMRs are central to nuclear growth but not a silver bullet. SMRs account for 77% of post-2030 capacity additions, yet high first-of-a-kind costs, region-specific supply chains, and unresolved licensing hurdles mean widespread cost parity with large reactors is unlikely before the 2040s. We expect initial implementation where large-scale nuclear or renewables are impractical, such as industrial hubs for steel, cement, and petro-chemicals, data centres, and in remote locations.

- The economic viability of nuclear hinges greatly on policy support. Government subsidies covering part of the cost through CfD, and/or government-backed loans, justified by energy security and decarbonization goals, are critical to new nuclear and essential to reducing the competitiveness gap with ever-cheaper renewables.

- Legacy challenges persist. High costs are foremost, but other structural barriers must be resolved for nuclear to sustain its resurgence including the efficiency, safety, and security of the fuel cycle and long-term waste disposal; proliferation safeguards; construction overruns; and an ageing workforce.

SMR vs Conventional nuclear by region
Units: GW



The case for nuclear

Nuclear power has long delivered steady, carbon-free electricity and was once viewed as a pillar of national energy independence. Faith in the technology was shaken by the 1979 Three Mile Island and 1986 Chernobyl disasters, which spurred anti-nuclear movements in several countries, particularly Germany and Italy. Then, the 2011 Fukushima Daiichi accident stalled new projects, accelerated Germany's phase-out, and exposed the industry's growing problems, especially in OECD countries: soaring capital costs, delays on complex third-generation plants, and intense competition from cheap gas and rapidly falling renewable prices.

However, rising geopolitical tensions are sharpening the focus on national and energy security, reigniting interest in nuclear power. Surging electricity demand from AI-driven data centres, transport, and decarbonization further strengthens the case. Finally, significant private capital investments and the promise of SMRs provide a potential pathway for lower costs and project risk. However, the nuclear industry cannot exist without close supervision from governmental (and international) bodies.

We expect global nuclear power generation to grow by 57% over the next decade (Figure 3.17). Output growth slows in the mid-2030s – not for lack of new projects, but because many older reactors are retiring. Starting in the late 2040s, however, rising electricity demand from AI, transport, and hydrogen production combine with more cost-competitive SMRs to spark a new wave of expansion that carries through 2060 and beyond. Most capacity added before 2040 will come from large, site-built reactors, many of which are already under consideration and early planning. After 2040, growth will be shared between these conventional units and factory-produced SMRs. From 2050 to 2060, 70% of all new additions will be based on SMRs, indicating a rapid surge in the latter part of our forecast. Nuclear generation continues to grow during the whole forecast period and reaches 6,500 TWh by 2060, about 150% above today's level. This means nuclear expands at a rate a little faster than electricity demand growth (+140%) over this period, underpinning its continued relevance in the power mix.

Nuclear power generation grows by 150% to 2060

Nuclear power generation by region (TWh/yr)

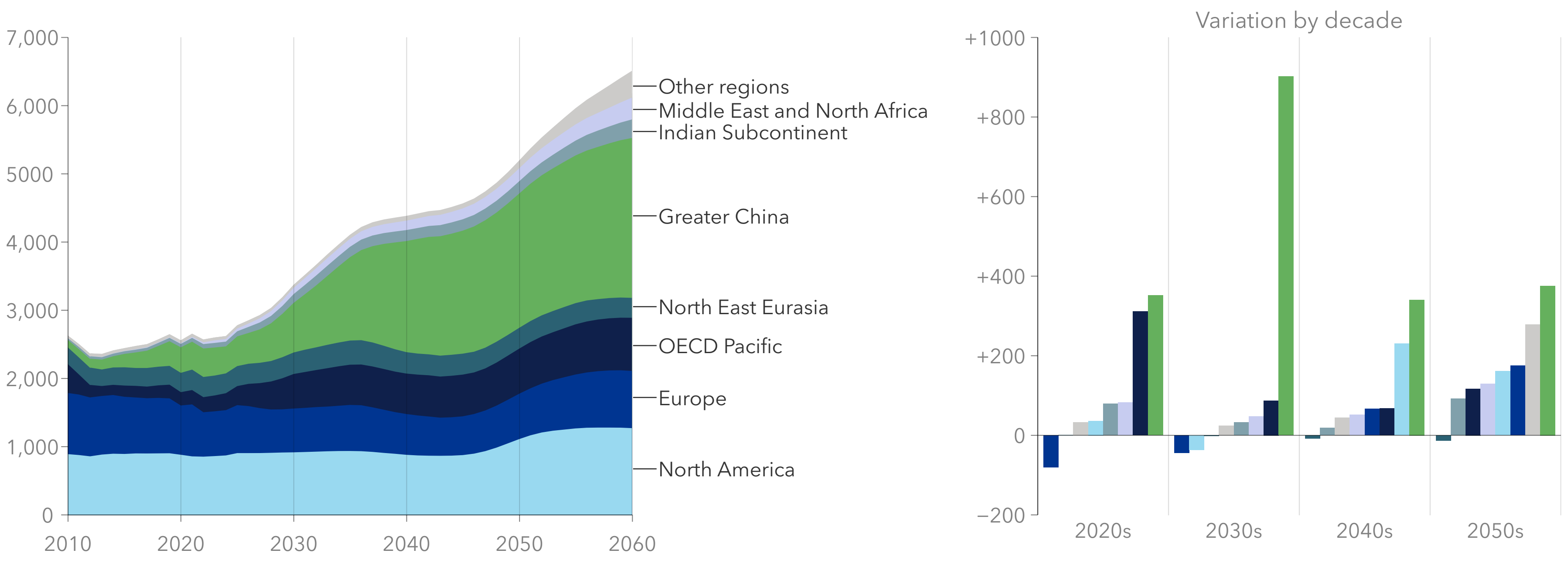


FIGURE 3.17 | Historical data source: IEA WEB (2025)

Generation costs will differ by region

In our ETO model, we compare generation costs using the energy-revenue-adjusted LCOE (Section 3.1) and find substantial regional variation for nuclear. For SMRs, material and labour intensity per megawatt rises as module size falls (Stewart et al., 2024). Accordingly, we assume first-of-a-kind SMR CAPEX is 60% higher than for conventional large-scale nuclear (LSN). Consistent with Abou-Jaoude et al. (2023), we apply a 10% learning rate for SMRs (unit cost reduction per cumulative capacity doubling). For LSN, we assume a 4% learning rate, reflecting future improvements as a consequence of significant efforts to reduce costs, despite the escalation in costs observed in OECD countries over the past decade.

Additionally, geopolitical tensions will influence how regions choose technology partners and supply – chains. We assume OECD countries will not accept Russian or Chinese technology and vice versa, while the rest of the world accepts an equal mix. Thus, the cost learning rates – and resulting cost reductions – are limited to each bloc's cumulative capacity expansion. This means that the SMR nuclear cost for OECD countries versus Russian and Chinese technology will develop differently for a range of LCOE before support and revenue adjustments (Figure 3.18).

We find limited evidence to support claims that SMRs will solve the cost hurdle in any meaningful way before the late 2030s. Depending on the level of

SMR costs decrease faster, but catch up only post 2040

Median levelized cost of nuclear electricity (USD/MWh)

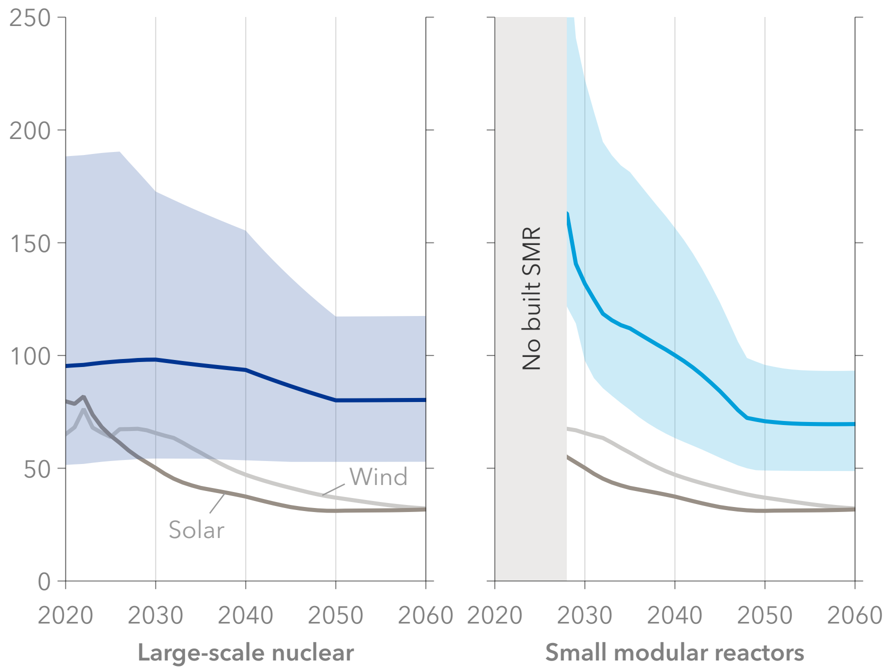


FIGURE 3.18 | Shaded areas represent regional LCOE ranges.

government support, projects can leverage capital at a lower cost or access another support scheme. This could tip SMRs into more favourable territory when compared with LSN, let alone other energy sources like solar or wind. However, based on our forecast we find that that LSN will still be less expensive per megawatt until about 2040 when mass production cost learning curves can bring down SMR costs and accelerate uptake.

Regional trends

North America, Europe, Greater China, and North East Eurasia currently generate most of the world's nuclear power. Within a decade, Greater China is poised to surpass Europe and North America in output. Japan and South Korea aim to double their generation by 2030 through new builds and reactor restarts. The Indian Subcontinent, Middle East and North Africa, and South East Asia will all expand their generation from modest levels to around 300 TWh each in 2060.

Several countries such as Bangladesh, Belarus, Turkey, Egypt, and the UAE have either just commissioned their first reactors or have projects in late-stage construction. Established nuclear countries are expanding their existing fleets or re-starting mothballed sites. After adjusting each project for its likelihood of completion, we estimate about 85 GW of firmly planned capacity is already in the pipeline. Beyond that, we expect another 880 GW to be built between now and 2060.

Half of the world's reactors are more than 30 years old and nearing the end of their original design lives. High decommissioning costs, lower-than-expected life-extension costs, and renewed energy-security concerns are pushing many governments to keep plants running longer. However, even with planned extensions, our analysis shows that over a 10-year period from the mid-2030s, retirements will almost match new builds, which keeps the global fleet stagnant at 650 to 700 GW. Post 2045, new additions will significantly add to the nuclear fleet which will reach 1,200 GW in 2060.

In our forecast, about half of new nuclear between 2030 and 2060 (410 GW) is based on SMR technology. However, SMR uptake will not really take off until the 2040s. The main reason for the initial slow uptake is that the first pilot projects will materialize by 2030 and provide feedback on the technology and costs. Scaling and still-high costs will limit growth compared with conventional nuclear. Meanwhile, unresolved challenges such as long-term waste management, security, enriched-uranium supply chains, proliferation safeguards, and workforce attrition are issues that the nuclear industry will need to address to enable the expected growth.

In our forecast, about half of new nuclear between 2030 and 2060 (410 GW) is based on SMR technology. However, SMR uptake will not really take off until the 2040s.

In addition to decarbonization, several factors will contribute to the future relevance of nuclear:

- **Energy security concerns**: Geopolitical shocks to energy supply, such as Russia's invasion of Ukraine and unrest in the Middle East, are driving nuclear's renewed appeal, especially in regions where infrastructure, expertise, and experience already exist. Plants require little fuel once operational, and uranium supply chains are diversifying (Roy, 2024; Gov.uk, 2024; Gardner, 2025). These tensions also shape technology supply, with OECD countries, Russia, and China each relying on domestic providers, while others take mixed approaches. India, aiming for 100 GW by 2047, has historically used Russian technology but is turning to French and US suppliers (WNN, 2025). We caution, however, that there is a difference between security of supply and physical security: the manifest ability of nuclear to provide firm power is undisputed, but the extent to which nuclear plants are vulnerable to natural catastrophes and malicious attack needs careful consideration (Squassoni, 2024).

- **Increased electricity demand and load growth due to data centre and AI energy consumption:** AI infrastructure requires constant, high-density, low-emission power that variable renewables struggle to provide without costly grid upgrades or large-scale storage. In the near term, renewables will dominate due to the lack of turnkey nuclear solutions, but nuclear is a strong medium- to long-term candidate. We project AI-driven demand to account for almost 30% of annual OECD load growth in the early 2030s – equivalent to the output of 10 utility-scale reactors each year. The emerging procurement strategies of cloud-service providers echo this logic: long-term nuclear power-purchase agreements (PPA) in the US (Oklo, Google, Microsoft etc.) are joining corporate renewable power purchase agreements as instruments to de-risk energy supply chains.

- **Biodiversity, land use, and grid connection advantages:** In regions already constrained by land use, biodiversity commitments, or insubstantial interconnections, nuclear's compact footprint and year-round capacity factor present a compelling alternative.

- **Novel market mechanisms de-risk nuclear development:** As the demand for power capacity grows due to hyperscalers, the need for constant supply necessitates novel procurement strategies such as long-term PPA and CfDs, which de-risk the private sector development of nuclear power. While nuclear is not a quick fix (high capital intensity and long lead times persist), its ability to provide 24/7 low-carbon reliable baseload power positions it to support the digital economy's energy requirements.

Is smaller better?

SMR technology is often promoted as the next generation of nuclear power. Private nuclear developers see SMRs as an opportunity to meet both energy security goals and AI demand.

Factory fabrication, modular construction, and passive-safety designs promise to compress on-site build schedules from today's seven-plus years to a more manageable three to six years, and to replace the 'mega-project risk premium' with learning-curve cost declines.

SMRs will need to fulfil this promise of cost competitiveness while maintaining very strict safety standards and effectively addressing challenges related to nuclear proliferation and waste management. This is a big ask, and the challenges stacked against SMRs should not be underestimated, particularly when renewable electricity is developing so rapidly, inexpensively, and at a scale which will see solar and wind responsible for three quarters of global electricity production in the space of a single generation. Nevertheless, we believe that SMRs will achieve commercial readiness well within our forecast period, and that there are important market positions for the technology.

SMRs excel where large-scale renewables are impractical:

- Maritime transport: SMRs used for direct propulsion on ships potentially offer a long-term energy solution compared with costly biofuels and e-fuels. However, significant technological, commercial, and regulatory challenges mean that nuclear in shipping only scales from 2045 in our forecast, though it accounts for 10% of the maritime fuel mix by 2060.
- Industrial heat and power: Many heavy-industry sites require reliable electricity plus high-temperature steam and, increasingly, on-site hydrogen production. A SMR can potentially deliver all three, switching between grid supply, process heat, and electrolysers as wind or solar output fluctuates.
- AI-driven data centres: Modern data centres need round-the-clock, high-density power with minimal interruptions. SMRs offer a high-capacity factor (over 90%), a compact footprint that fits on-site or alongside existing campuses, and low transmission losses because they can be sited close to the load. Their modularity lets operators add reactors in increments that match new server halls, avoiding the massive upfront outlays of gigawatt-scale plants.
- Cost and flexibility: By balancing grid exports, industrial demand, and hydrogen production, a SMR can keep capacity factors high and levelized costs competitive. During periods of cheap renewable generation, the reactor can throttle back or redirect output to hydrogen, then ramp up to cover shortages – precisely the flexibility heavy industry and data-centre operators value.

In short, SMRs could provide the dependable, scalable, and versatile energy backbone required for both hard-to-electrify industries and the always-on computing infrastructure that underpins AI.

3.5 HYDROPOWER

Hydropower electricity generation will grow 53% from today to 2060, with almost two-thirds of this growth occurring in the next decade. Hydropower's share of global electricity generation will surpass fossil's from the early 2050s, but its overall share will shrink, overshadowed by the expansion of solar and wind. Pumped hydropower will play an increasingly important role as a flexibility provider to the grid, but batteries are more cost competitive and will grow much faster.

Electricity generation
By 2060, hydropower will contribute 8% of global electricity generation, roughly equal to nuclear, while combined electricity from fossil fuels will have shrunk to 3%. While hydropower's share in the 2060 power mix is smaller than it's 14% share today, it will play a valuable role as both an emission-free energy source and as a source of dispatchable power capable of quickly adjusting output to balance variable renewable generation.

Hydropower will grow in most regions to 2060
Hydropower generation in selected regions (TWh/yr)

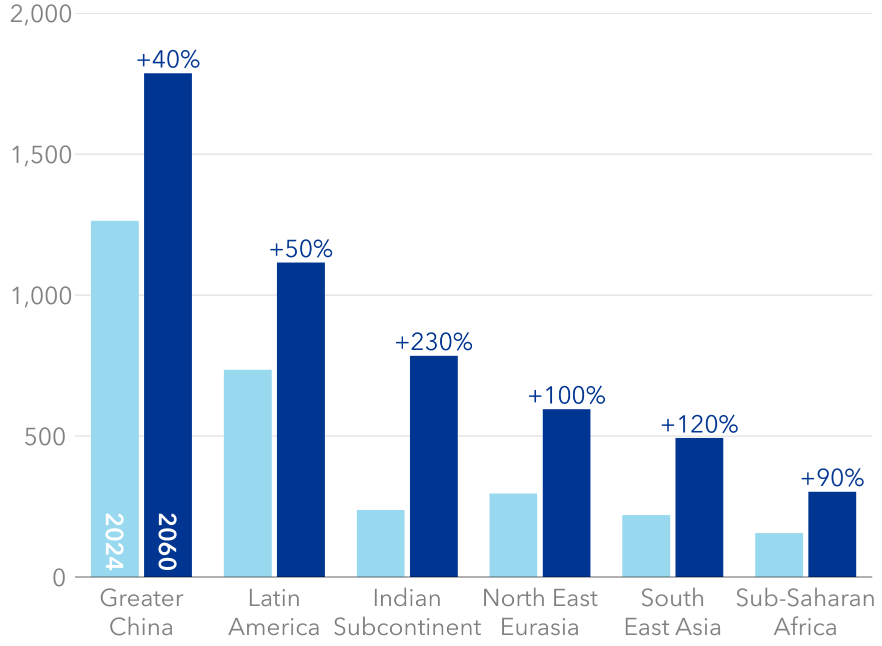


FIGURE 3.19 | Generation in the rest of the world grows 7%.
Historical data source: IEA WEB (2025)

In Greater China, hydropower will grow 41%, but its share of electricity generation in the region will decrease from 12 to 8%. India will triple its hydropower generation, ending at 7% of the regional demand at the end of the period.

What's hampering hydro growth?

Hydropower is limited by the number of technically suitable sites and by biodiversity and other conservation considerations. While hydropower mainly generates electricity, some reservoirs also support irrigation and flood control – roles that are increasingly vital as climate change intensifies extreme weather events. Balancing conservation with climate adaptation is complex; for example, recent Norwegian regulation (Hjort, 2025) now allows new hydropower projects in previously protected areas to mitigate flood risk, signalling a possible shift in priorities.

Hydropower experienced severely reduced generation in several regions in 2023 due to drought. Despite recovering with a 10% global increase in generation in 2024 (IHA, 2025), global warming is introducing significant uncertainty into the business case for hydro and limiting its buildout. Zambia and Zimbabwe, two countries heavily reliant on hydropower, are in the midst of an energy crisis due to a prolonged drought in 2024, leaving both nations scrambling to diversify their energy sources.

Pumped hydro as a flexibility provider

Pumped hydropower is currently the largest source of energy storage. It is an ideal medium-duration storage provider that can store large amounts of energy for hours to days with high efficiency by pumping water up in surplus periods and releasing it to produce electricity when needed. Electricity generation from pumped hydro will double from 2024 to 2030, growing from 0.8 to 1.3% of global electricity demand. After 2030, the growth rate slows due to competition with more cost-competitive battery energy storage systems (BESS). Batteries installed for short-duration storage, mainly to shift solar or wind output a few hours to peak demand times, can partly act as medium-duration storage (DNV, 2025). Here, batteries will also be able to manage price fluctuations in electricity markets, also known as arbitrage, which has typically been the main driver for pumped hydro expansion. A recent study on the economic outlook for pumped hydro in China also concludes that it will lose financial competitiveness on arbitrage to batteries, meaning hydropower will need capacity fees, call options, or other alternative revenue streams to remain attractive (Peng, 2025). BESS will surpass pumped hydro as the largest flexibility provider in the early 2040s, and by 2060 pumped hydro will deliver only 1.0% of electricity demand whereas BESS will grow to 2.5%.

While run-of river installations cannot store energy in the form of water, they can use battery storage to harvest the river's energy potential and sell electricity at price-attractive times (IHA, 2021). One Norwegian utility (Å Energi, 2025) has started building a hydropower facility that uses excess electricity produced when prices are low for hydrogen production.

Batteries outcompete pumped hydro in the long run
World storage capacity by technology (TWh)

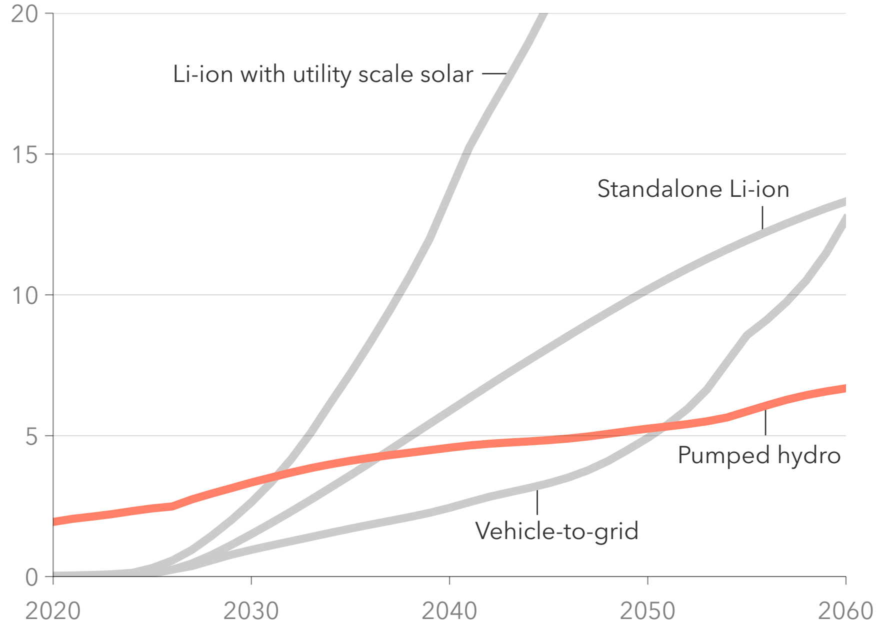


FIGURE 3.20 | Historical data source: GlobalData (2025)

3.6 POWER GRIDS

Grid bottlenecks: what's happening?

- Grids are congested, leading to high congestion charges and missed economic growth. In 2023, more than USD 1bn was spent to curtail wind farms in Scotland and replace lost output with gas generation in England. Distribution networks also face growing constraints as EV and heat pump uptake rises.
- New connection requests are piling up. Waiting times to connect to transmission grids have doubled or trebled over two decades. In the US, the median delay is five years; in Europe, some projects need to wait over a decade. Difficult decisions on who to connect first (e.g. data centres or new schools) are emerging.

Grid readiness lags transition speed

- Transmission capacity is not keeping pace with the increase in demand. In high-income regions, flat load meant few upgrades were needed and existing grids absorbed early renewables. However, rapid growth in renewables, storage, data centres, green industry, EVs, and heat pumps requires urgent expansion.
- Planning remains slow. Many transmission system operators (TSOs) still assess projects one by one, redoing studies when other projects drop out, though some are shifting to cluster-based methods where projects are assessed in groups. Permitting delays, long delivery time for equipment, long build times, and unclear cost-sharing rules add to the friction.

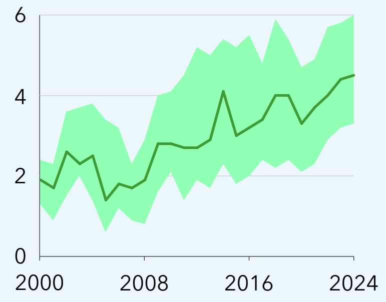
How did we get here?

- Past demand signals discouraged grid investment. A brief transformer boom in the 2000s collapsed after 2008, making manufacturers cautious. Today, lead times often exceed three years, reaching eight years in Europe. Sourcing is further constrained by many countries avoiding foreign suppliers over cyber concerns.
- Previously, system operators had little incentive to plan. Regulatory models favoured cost-cutting over anticipation. Ageing control rooms remain common and the small number of dominant equipment vendors slows progress, locking in inertia just as new loads and renewables surge. The concomitant risks were clearly revealed by the April 2025 outage in Spain.

5 years

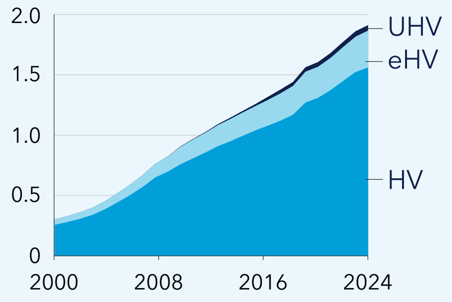
Average time for US renewable project from request to operation

US transmission grid waiting times (yr)

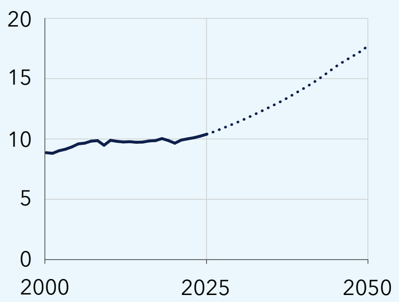


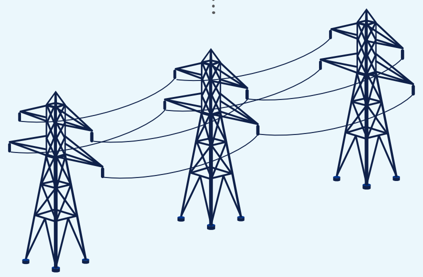
Source: LBNC (2024), Range shows p25/p75

CHN Transmission lines (Million ckm)

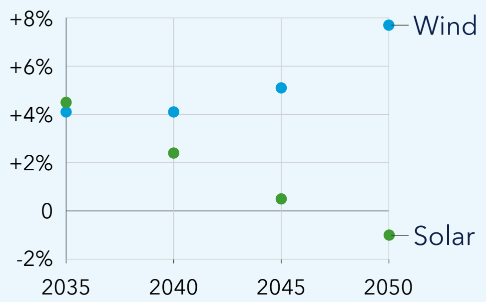


Electricity demand in high income regions (PWh/yr)

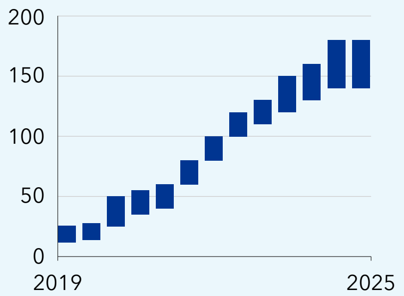




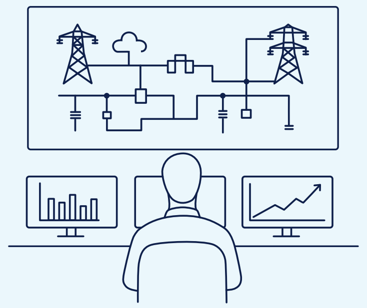
Renewables without grid bottlenecks



Transformer lead times in the US (weeks)



Source: DOE, Wood Mackenzie, NREL



4%

How much higher 2035 global solar and wind capacity would without grid constraints

Grid constraints are unevenly felt

- Grid bottlenecks are not universal. China expanded rapidly through strong central planning and domestic transformer supply. Ultra-high-voltage lines link remote renewables to demand centres, avoiding many delays seen in Europe or North America. Some middle-income countries with more centralized systems, like Vietnam and Turkey, also manage better.
- Low-income countries face different challenges: limited capital, weak institutions, and security risks like cable theft. Their issue is not congestion, but underdeveloped grids that struggle to support electrification or integrate decentralized generation.

Do grid bottlenecks hold back energy transition?

- Yes, particularly in high-income regions. Without grid constraints, our model shows global solar and wind additions would be 4% higher over the next decade. The regional effect is sharper: by 2035, solar capacity in Europe would be 16% higher; wind capacity 8% higher in Europe, 10% in North America, and 14% in OECD Pacific.
- These results align with IEA estimates of a 10 to 20% impact. Wind remains constrained into later decades, while solar redeploys to less congested regions. Delays and uncertainty are also likely to slow decarbonization in manufacturing.

What can be done?

- Grid-enhancing technologies, storage at chokepoints, and new market models can provide short-term relief, but are no substitute for systemic change. Most control rooms rely on ageing systems, and operators remain risk averse. Planning must shift from reactive approvals and connection philosophy to a holistic, early, continuous expansion with clear investor visibility and credible cost recovery.
- Financing also plays a role. Grid assets need long-term planning and stable returns. Governments and financing institutions can help de-risk early stages, but reforms in planning and regulation will matter more.

Grid bottlenecks

The grid is now the bottleneck

Transmission and distribution systems built for stable, centralized power are not designed to accommodate the rapid growth in renewables, EVs, data centres, and heat pumps. In many regions, the grid is no longer a background enabler. It is the constraint.

This is not an abstract risk. In 2023, the UK spent over USD 1bn curtailing wind farms in Scotland and replacing the lost output with gas generation in England due to transmission limits (Simakov, 2023). In Texas, monthly congestion costs passed USD 2bn (Potomac Economics, 2024). These costs are a direct result of electricity not reaching where it is needed, despite being available.

With many countries now increasing their renewable targets and auction volumes, these bottlenecks are becoming the rate limiter. Clean power is available, but it cannot be delivered.

Projects are delayed, and the impact is visible

New generation is stuck waiting. In the US, the median wait to connect to the grid rose from under two years in 2008 to five years in 2022 (LBNL, 2025). Some US areas now report delays of nine years or more (NREL, 2024). In parts of Europe, developers face waits beyond a decade, even for projects that are otherwise ready to build.

These delays are not only logistical: they shape the trajectory of the energy transition. In our model, removing grid constraints raises solar and wind deployment in the next decade by about 4% (Figure 3.21). In high-income regions, the impact is more pronounced. By 2035, Europe would have 16% more solar and 8% more wind capacity than in our baseline forecast. These shortfalls also create reinforcing feedback loops: slower buildout weakens investor confidence, reduces learning effects, and delays cost declines – making it harder to catch up later.

Wind is more constrained because it tends to be developed in larger blocks and in more remote areas. Solar has greater siting flexibility and can shift more easily to unconstrained regions.

Renewables 4% higher to 2035 without grid constraints

Sensitivity to removal of grid constraints

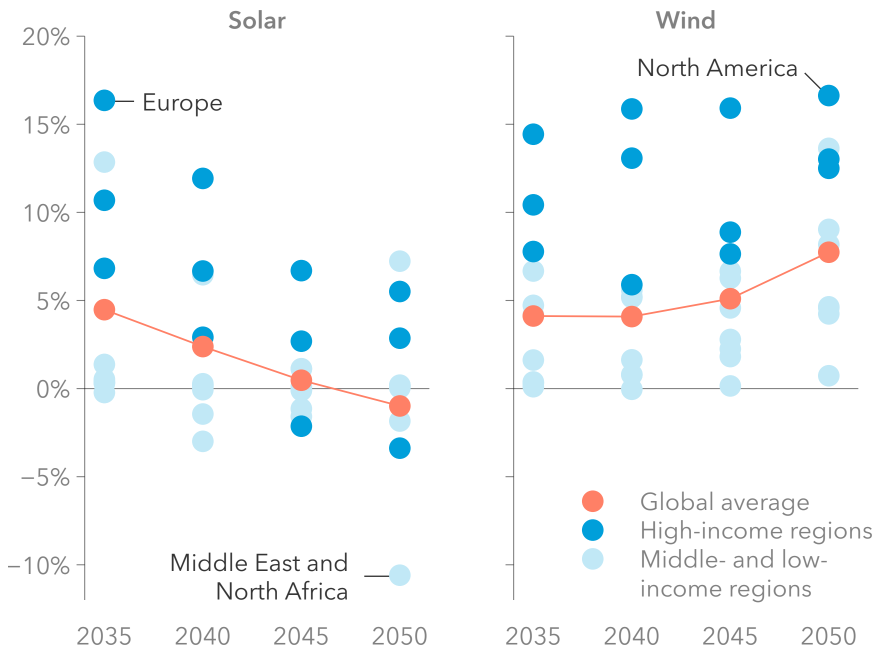


FIGURE 3.21 | Each dot represents a region. North America, Europe, and OECD Pacific are classified as high income regions.

Why is the grid falling behind?

There are practical limits. After a brief transformer boom in the 2000s, demand fell sharply post-2008 and manufacturers stopped investing. Now that demand is surging, supply cannot respond quickly enough. In North America, lead times for large transformers often exceed 130 weeks and can stretch to four years. Security concerns limit sourcing, as many countries avoid foreign equipment.

These bottlenecks also reflect systemic issues. Planning is reactive. Grid operators often assess connection requests one at a time. If a project drops out, studies must be redone. Some regions are shifting to cluster-based methods, but change is slow.

Control rooms are part of the problem. Many still rely on ageing software and procedures designed for inflexible systems. Operators, trained in reliability risk avoidance, are slow to accommodate variability. A lack of competition among vendors has also made modernization of control rooms costly and uneven.

Relief is possible, but not automatic

Grid-enhancing technologies (GETs) offer a way to ease congestion. Dynamic line ratings, flow control devices, topology optimization, and reconductoring are already unlocking capacity in places like Germany, India, and the US. Storage also helps, especially near chokepoints. However, these tools are only part of the solution.

Advanced software is becoming just as important. Human-AI systems support grid operators by speeding up power flow calculations and improving dispatch decisions, especially as the grid becomes more dynamic. Rather than replacing existing tools, AI helps make them faster and more adaptive. This reduces losses, cuts renewable curtailment, and eases congestion. Lightweight models provide near-optimal results quickly, which legacy systems can then finalize.

Operators are also starting to use AI to manage flexible demand, detect faults, and improve resilience. These tools can reduce the need for redundant infrastructure and help grids run closer to their capacity, but adoption remains slow. Fragmented responsibilities, risk-averse institutions, and unclear incentives are now bigger obstacles.

Planning ahead reduces risk and cost

Unlocking capital is important, but the deeper issue is credibility. Conventional project finance models struggle with grid assets, which have long lead times and regulated returns. Public sector involvement, especially from development finance institutions, can help manage early-stage risk. Above all, the system needs predictability. Since development timelines differ, it is difficult for the regulated part to know up front where, when, and how much generation and demand is planned.

Multi-year investment plans, transparent connection rules, and early signals allow developers to act with confidence. Fixing congestion is challenging, but it is doable and essential.

Physical infrastructure

Historically, power grid capacity has grown in line with peak electricity load (Figure 3.22). TW-km reflects active power transmission capacity over distance. It combines how much electricity can be transferred (in terawatts) with how far it can be moved (in kilometres).

The spatial distribution of supply and demand points influences how closely transmission needs track peak load. For much of the past, peak demand has served as a reasonable proxy, but this relationship is weakening. Recent grid expansion has been driven by the need to handle greater variability and ensure system stability by connecting solar and wind projects (which are often more dispersed than conventional plants) and strengthening grids within countries and across borders.

Europe is furthest along in this shift. Transmission growth has outpaced peak load since 2008, reflecting a mix of domestic reinforcements and international interconnectors. Examples include COBRAcable (700 MW, Denmark–Netherlands) and the North Sea Link (1.4 GW, UK–Norway), both aimed at improving flexibility and sharing surplus renewable power (ENTSO-E, 2021). Similar investments are now emerging elsewhere. In China, the Gansu–Zhejiang UHVDC line delivers wind and solar power over 2,000 km from inland desert regions to the eastern industrial centres – a large-scale example of renewables integration and grid strengthening combined (IEA, 2022).

Despite short-term constraints, particularly in Europe and North America where permitting and supply chain delays continue to slow project delivery, we project sustained and widespread grid expansion through to 2060 (Figure 3.23). Transmission line length is set to nearly triple, driven by rising electrification, changing spatial patterns of supply and demand, and the operational needs of variable renewables. While the bulk of new builds occur in Asia, high-income regions also see renewed growth after a period of stagnation – not because demand is rising rapidly, but because the system is changing beneath it.

We also expect a gradual shift in technology. High-voltage direct current (HVDC) lines, still only 1% of global transmission length today, will reach 5% by 2050. This supports long-distance, cross-border and offshore integration, particularly in China, India, and parts of Europe.

Distribution networks will follow a similar trajectory, doubling in length by 2050. In low- and middle-income regions, this growth is driven by new connections and spatial expansion. In high-income regions, it reflects asset renewal and the increasing role of distribution in system flexibility and balancing. As investment needs grow, attention is turning to how costs are recovered. This places network charges at the centre of the debate. While grid charges rise by USD 29/MWh to 2060, wholesale electricity prices fall by USD 66/MWh over the same period. This means that nearly half of the cost benefit of switching to a renewable-based power system will be offset by rising grid-related charges. As investment needs grow, attention is turning to how costs are recovered – placing network charges at the centre of the debate, and reshaping electricity affordability worldwide.

High voltage direct current (HVDC) lines, only 1% of global transmission length today, will reach 5% by 2050.

Transmission capacity grows broadly in line with peak load
Peak electricity load and transmission capacity by region

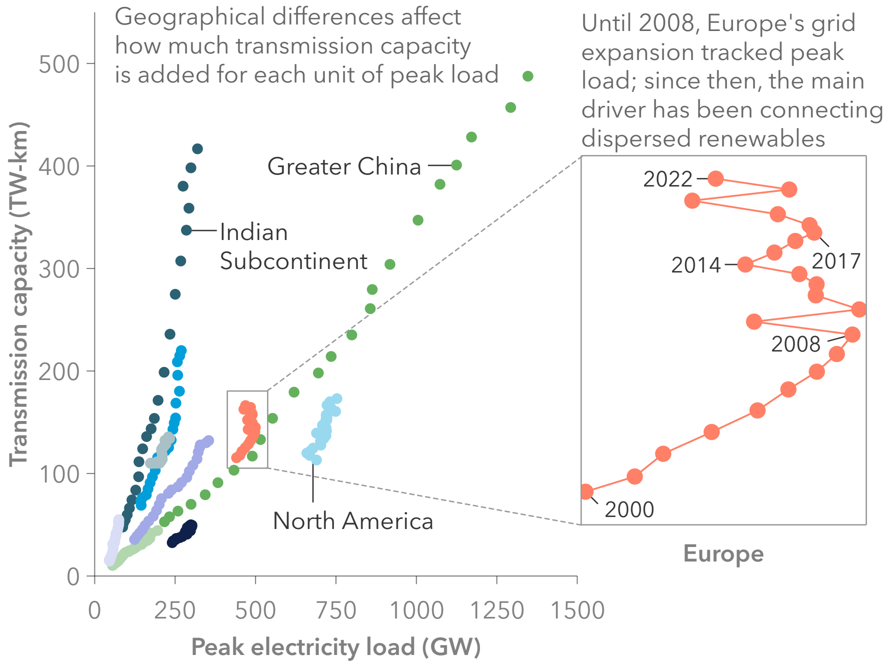


FIGURE 3.22 | Data shows years 2000 to 2022.

Power grids are set to grow 2.4 times in length by 2060, led by growth in Asia
Transmission and distribution power line length by region (Million circuit-km)

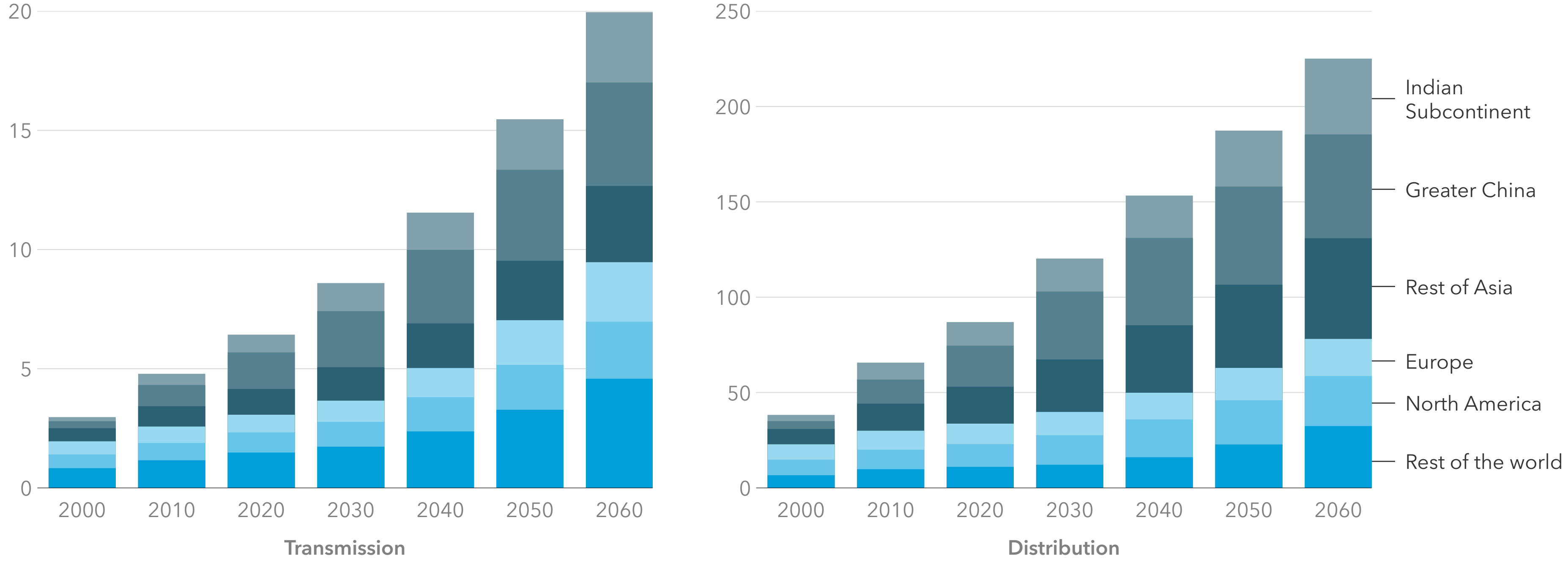


FIGURE 3.23 | Historical data source: GlobalData (2025)

Expenditures and network charges

Global investment in electricity grids is currently around USD 400bn/yr (IEA, 2025b) and covers transmission, distribution, digital infrastructure, and grid support functions. With growing network length and complexity, total expenditures are rising. We project combined investments and operating costs to reach USD 600–700bn/yr in the 2030s, and close to USD 1trn/yr by the 2050s (Figure 3.24). Operating expenditure (OPEX) is set to double from USD 300bn/yr to USD 600bn/yr. Transmission accounts for 30 to 35% of total investment.

These costs are ultimately passed on to end users. In addition to investment recovery and OPEX, system operators increasingly charge for a broader set of services:

- Ancillary services such as frequency regulation, spinning reserves, inertia support, and black start capability
- Capacity payments to ensure firm supply in systems with falling price duration curves
- Loss compensation, congestion management, and curtailment costs
- Grid access and connection charges, particularly for distributed energy resources

As these components grow in cost and coverage, unit grid charges are rising faster than electricity demand. We project the global average grid charge will increase from USD 45/MWh today to USD 74/MWh by 2060 (Figure 3.25). We estimate that around three quarters of this increase is driven by expanded capacity payments that are needed to ensure stable revenue streams in systems increasingly dominated by zero-marginal-cost generation. As solar and wind set wholesale prices for longer durations, market revenues alone will no longer suffice to cover total system costs. This will require reform and redistribution, much of which will be reflected in end-user tariffs.

While grid charges rise by USD 29/MWh to 2060, wholesale electricity prices fall by USD 66/MWh over the same period. This means that nearly half of the cost benefit of switching to a renewable-based power system will be offset by rising grid-related charges.

The redistribution of costs highlights a structural shift in power markets. Historically, consumers benefited directly from falling generation costs, but in a renewables-dominated system, grid infrastructure and balancing services become the dominant expenditure. This raises questions of fairness and efficiency. Industrial users with high load factors may benefit most from lower wholesale prices, while households and small businesses bear a proportionally higher share of rising network charges. Policymakers will need to design tariff structures that reflect not just consumption but also system value – for example, rewarding flexible demand that eases congestion and reduces the need for costly backup. At the same time, greater transparency in cost allocation will be critical to sustain public support for electrification. If rising grid charges are perceived as hidden taxes, opposition could slow investment. Ensuring that the economic gains of a decarbonized power system remain visible to end users is therefore as important as building the physical infrastructure itself.

Grid expenditures to more than double by 2050s

Average annual grid expenditures by decade (Billion USD/yr)

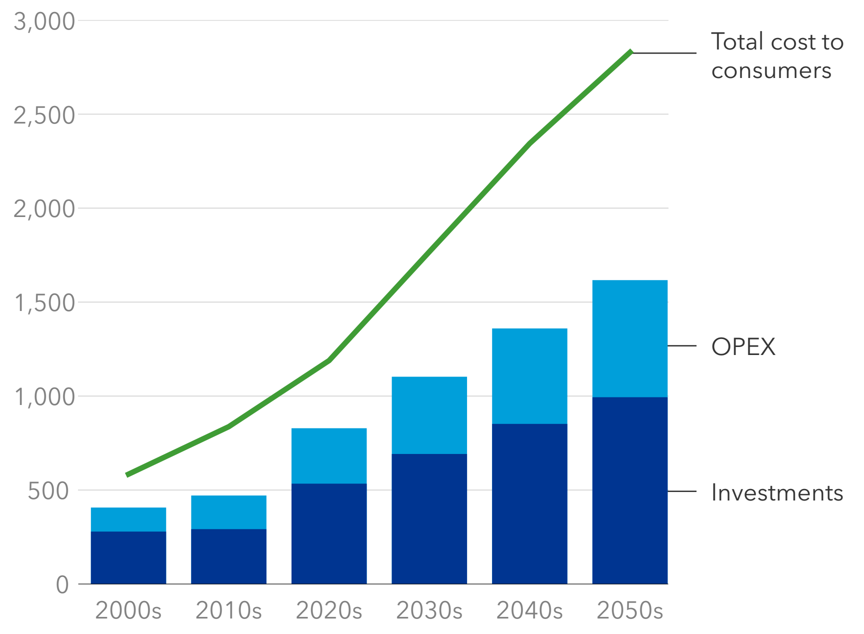


FIGURE 3.24 | Each bar shows average yearly spending within each decade.
Historical data source: DNV estimates based on IEA, GlobalData

Rising grid charges will absorb much of the benefit from falling wholesale prices

Average grid charge globally and by region (USD/MWh)

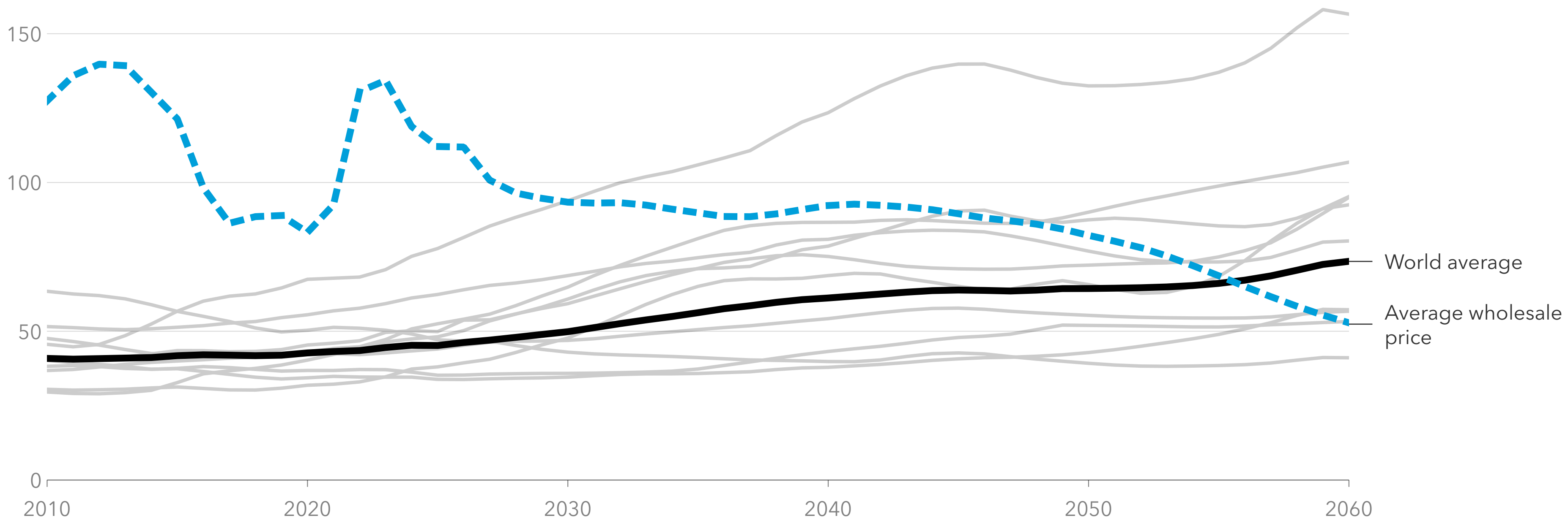


FIGURE 3.25 | Each grey line shows the average grid charge by region, averaged across residential and industrial users.
Historical data source: DNV estimates based on data from ENTSO-E (2025), EIA (2025), IEA (2024), and local sources

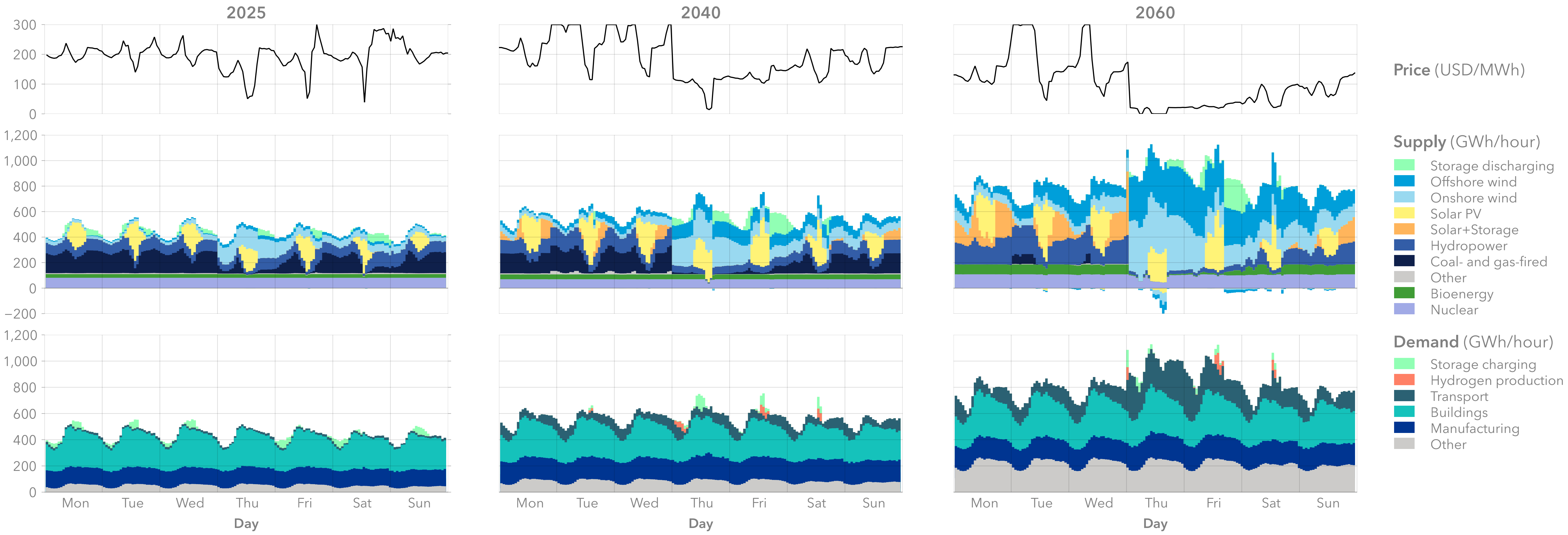
The power of the hour: how prices move in a high-renewables system

Electricity systems are driven by hourly dynamics that annual aggregates cannot show. To illustrate this, we analyze one winter week (Week 3) in Europe in 2025, 2035, and 2050. Using repeated weather and demand patterns, our system dynamics model traces how the balance of technologies shifts over time and what this means for wholesale prices. The snapshots reveal how today's fossil-fuelled mix gives way to a system dominated by renewables, and how this transition alters both the level and volatility of prices.

Why hourly modelling matters

Annual or monthly averages hide the swings that set investment signals, define the value of storage and flexibility, and determine how often curtailment occurs. Our approach combines system dynamics with full hourly dispatch across supply, storage, prosumer behaviour, and flexible demand. This allows a direct reading of how technology mix and operating constraints translate into price outcomes.

Simulated hourly dispatch in the European power system for Week 3 in years 2025, 2040, and 2060



2025
Fossil fuels still anchor Europe's stack. During calm, overcast hours, gas plants set the marginal price and can lift wholesale electricity above USD 120/MWh. When wind and solar conditions improve, renewable output pushes prices down towards zero for several consecutive hours. Storage charges quickly in these troughs. Prosumers also start to matter. What we show as demand is the grid-connected load after prosumer self-consumption. When rooftop PV output exceeds on-site use, prosumer feed-in increases supply onto the grid, reinforcing low-price hours. Overall, prices mostly sit in a USD 0–150/MWh band, with volatility visible but contained.

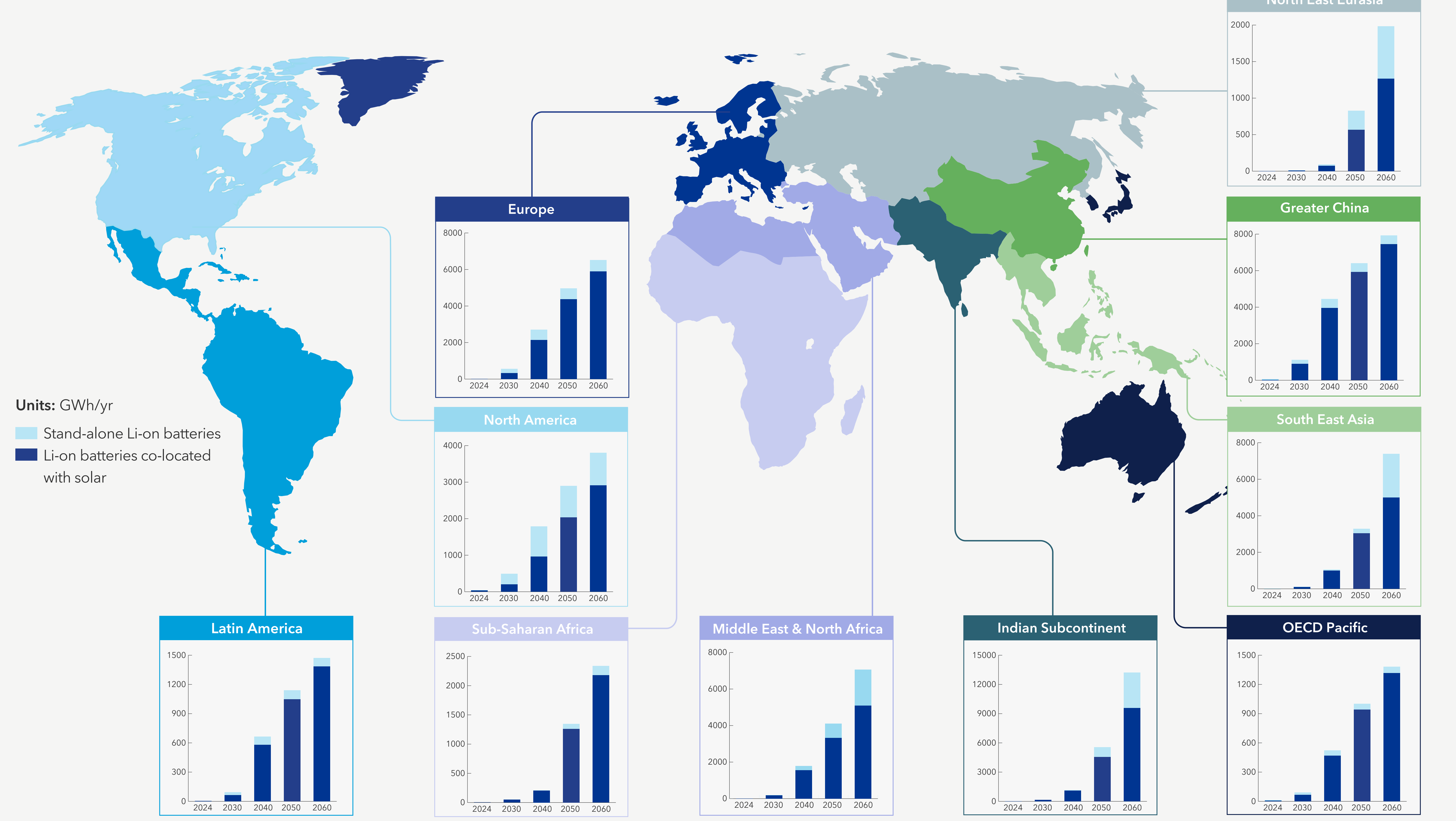
2040
Higher renewable capacity magnifies the pattern. Hours with surplus wind and solar become more frequent and prices touch zero far more often. Prosumers play a larger role in shaping the net load seen by the grid: self-consumption trims daytime peaks in grid-connected demand, while feed-in adds to supply during sunny spells. This would be even more visible on a summer week. Flexible loads such as hydrogen electrolysis and EV charging exploit low-price periods, yet curtailment appears more regularly once batteries are full. In weeks with weak wind and muted solar, reliance on gas sharpens scarcity pricing, with peaks above USD 250/MWh. The price profile is now lower on average and more volatile, reflecting both abundance and intermittency.

2060
By 2060, renewables dominate Europe's generation. In periods of low wind, residual demand on the grid remains high through the day and into the evening, even with daytime solar and the evening contribution from solar+storage. Wholesale prices are therefore elevated across many hours, not just at the peak, and scarcity spikes occur. These price signals draw thermal and hydropower generators to maximise output, providing firmness when variable renewables are scarce. At the other extreme, when wind and solar are abundant and storage is filling or full, wholesale prices sit near zero and at times turn negative. This also attracts hydrogen producers. Prosumers shape net load via self-consumption and feed-in, but the main drivers of extremes are renewable availability and the response of dispatchable plants. Curtailment becomes a feature in very high-renewable weeks.

3.7 STORAGE AND FLEXIBILITY

- Grid-connected energy storage capacity is expected to double between 2024 and 2030, increase eight-fold by 2040, 16-fold by 2050, and a staggering 25-fold by 2060 (2.4 TWh in 2024 to 60 TWh in 2060), largely to support the seven-fold growth in renewable electricity over the same period.
- While pumped hydro currently makes up the lion's share of the storage capacity (93% in 2024), by 2030 its share reduces to half of global storage capacity. By 2060 pumped hydro will only account for 10% of the global storage capacity.
- Batteries, specifically Li-ion batteries, are poised to take over from pumped hydro as the foremost storage provider, thanks to deep cost declines expected in the near future. The average global levelized cost of storage flexibility from a stand-alone utility-scale Li-ion battery will reduce from about USD 370/MWh in 2024 to USD 235/MWh by 2030, and about USD 155/MWh by 2050.
- Cost declines driven by China's Li-ion manufacturing capabilities will enable global adoption. Regions importing batteries or components from China, including North America, have benefited and will continue to benefit from compressed cost curves.
- In the near term, tariffs and trade barriers may dampen Li-ion adoption in regions like North America and Europe. However, in the medium to long term, we expect batteries for 2 to 4 hour applications to remain the most cost-effective storage solution globally.
- Risks related to critical mineral supply chains remain a concern for battery adoption, given the geographic concentration of mining and processing. However, ongoing advances in battery chemistry may alleviate these risks by shifting toward more abundant and less geopolitically sensitive materials.

Battery adoption increases around the world, with regional differences, enabling renewable energy penetration



Energy storage: the backbone of a flexible, renewable power system

As power systems evolve to integrate more variable renewable energy sources (VRES), electricity storage emerges as a critical enabler of grid stability and flexibility. Historically, pumped hydro has dominated utility-scale storage, but its growth is constrained by geography and environmental concerns. For scale, nine tenths of global energy storage capacity in 2024 was pumped hydro. However, by 2030 pumped hydro's share will reduce to half of global energy storage and by 2060 will be just one tenth. This technological transition is predicated on the cost-effectiveness of Li-ion batteries.

Li-ion batteries now lead the transition, offering fast-response flexibility, short-duration firm capacity (up to 4 hours), and services like frequency regulation and reserve replacement. Even in 2025, almost two-thirds of all energy storage additions globally are batteries. By 2060, we project global Li-ion capacity will reach 53 TWh, much of it co-located with solar plants to shift mid-day generation to evening peaks.

Cost trends of Li-ion batteries support this battery revolution. We expect the global scale of the levelized cost of storage of Li-ion batteries to fall below USD 200/MWh by early 2030s, from about USD 370/MWh in 2024, despite regional differences due to battery and component production capacities and trade headwinds. Supply chain volatility driven by critical minerals and geopolitical risks could temper short-term progress in regions such as North America (Blois, 2025) and Europe (Lombardo et al., 2025). Innovation in chemistries and recycling will be key to managing material constraints (Donback, 2025). Regions predominantly dependent on Greater China will see their battery costs falling consistently.

While other short-duration battery chemistries are emerging (such as sodium-ion), we expect lithium-ion batteries to maintain their dominant position. This is largely due to their first-mover advantage, the maturity of their manufacturing and processing infrastructure, and the economies of scale achieved through years of profitable operation. These factors create high barriers to profitability for alternative chemistries and reinforce a degree of technological lock-in.

EVs, V2G, and Prosumer Flexibility

Utility-scale Li-ion batteries, whether stand-alone or paired with solar, are not the only way batteries support the future electricity system. EV batteries, through vehicle-to-grid (V2G) technology, also offer valuable flexibility by acting as mobile energy storage that can supply power during periods of scarcity caused by weather events or daily demand fluctuations.

We forecast V2G energy storage capacity surpassing 10% of the total energy capacity of global storage, by 2029. By 2040, V2G storage will surpass pumped hydro, and by 2050 it will reach one-fifth of the total storage capacity available world-wide and maintain that position in 2060.

V2G is just one technology in the arsenal of the rising portfolio of prosumer technologies, such as BTM storage, and other technologies capable of demand response. These can all be aggregated to make virtual power plants (VPP). Advanced software enables decentralized assets such as distributed solar panels, batteries, and smart appliances all to operate collectively and respond in real time to grid needs.

Pumped hydro's share of global energy storage falls from 90% in 2024 to 50% in 2030. It will be just 10% in 2060.

Levelized cost of storage of Li-ion batteries on average continue to decline, despite regional variations in the short term

LCOS of stand-alone utility-scale Li-batteries (USD/MWh)

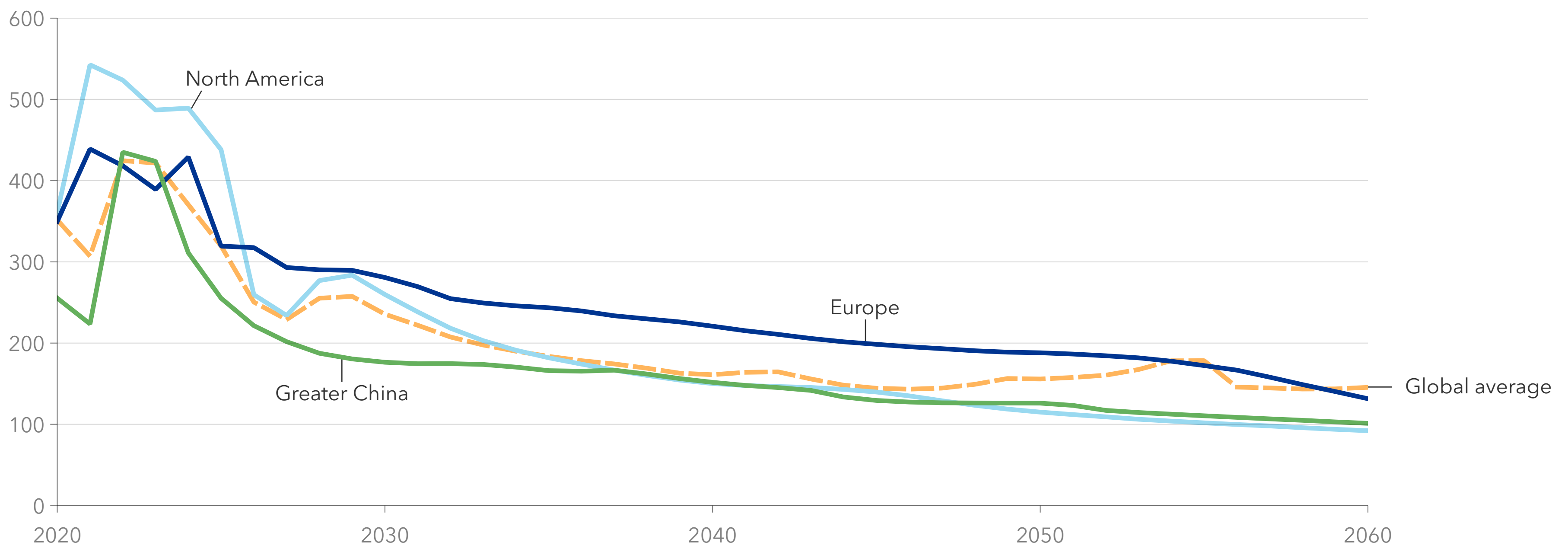


FIGURE 3.26 |

Building a flexible grid for the future

Flexibility, defined as the grid's ability to respond to short-term variability, is essential as renewables grow. In 2024, thermal plants covered nearly two-thirds all short-term flexibility needs in the global power system. Following thermal power plants, hydro power and pumped hydro were the second largest provider of short-term flexibility. Li-ion batteries will overtake hydropower by 2034. By 2047, batteries in all their forms – utility-scale connected to the grid centrally, distributed storage with rooftop solar, and EV as V2G – will provide 50% of the flexibility needs. By 2060, many thermal plants will face economic headwinds as clean energy undercuts their marginal costs and will only play a marginal role in providing short-term flexibility.

Not only will the sources of flexibility change, but the absolute demand for flexibility will also increase. Absolute demand for flexibility is measured by the extent to which output from dispatchable generation must change each hour within a day, relative to the average deviation in output over that day. This hourly difference from the daily average highlights the level of operational adaptability required from the system to sustain grid stability. From the 544 GW of flexibility needed globally in 2024, flexibility demand doubles by 2035, reaches 1,500 GW by 2050, and settles at three-fold (1,600 GW) globally by 2060. This increase is not universally applicable for all regions throughout the forecast period.

Flexibility needs rise sharply and plateau around 2040 in North America, Europe, and Greater China, driven by early, front-loaded deployment of variable renewables. In the rest of the world, the need grows steadily. By 2060, Li-ion batteries become the dominant source of flexibility across all regions, replacing declining thermal capacity, which falls rapidly after 2035 in Europe and Greater China. Thermal power lingers longer in the rest of the world where the transition is slower. Hydro remains stable but plays a limited role. Overall, we expect a global pivot toward battery-based flexibility anchored by Li-ion technologies.

Li-ion batteries overtake thermal power by 2039

Global storage capacity by type (GW/yr)

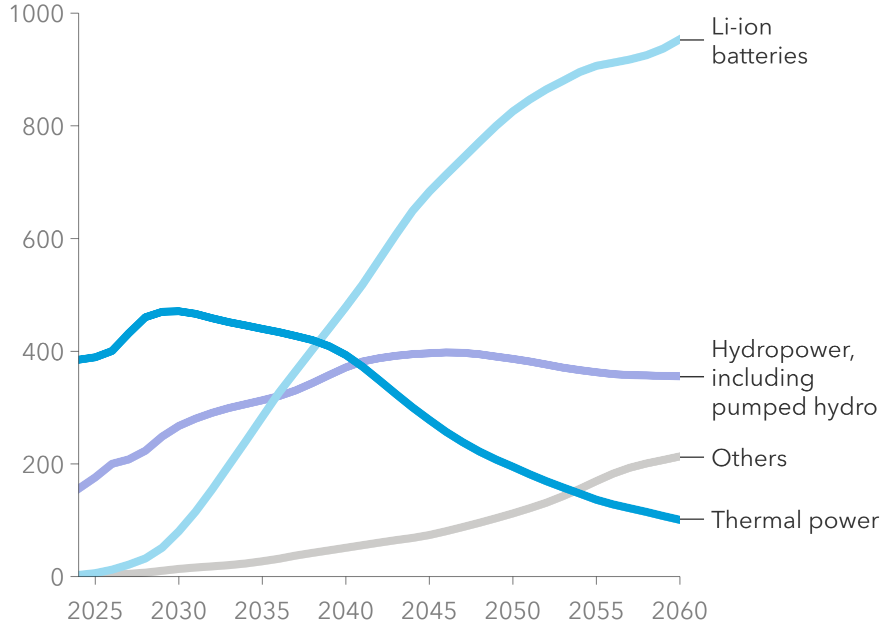


FIGURE 3.27 | Others includes power-to-H_2, nuclear, and long-duration storage; Li-ion batteries include utility-scale, distributed BTM, and EV V2G batteries.

Absolute demand for short-term flexibility increases, albeit with regional variations

Storage capacity in select regions (GW/yr)

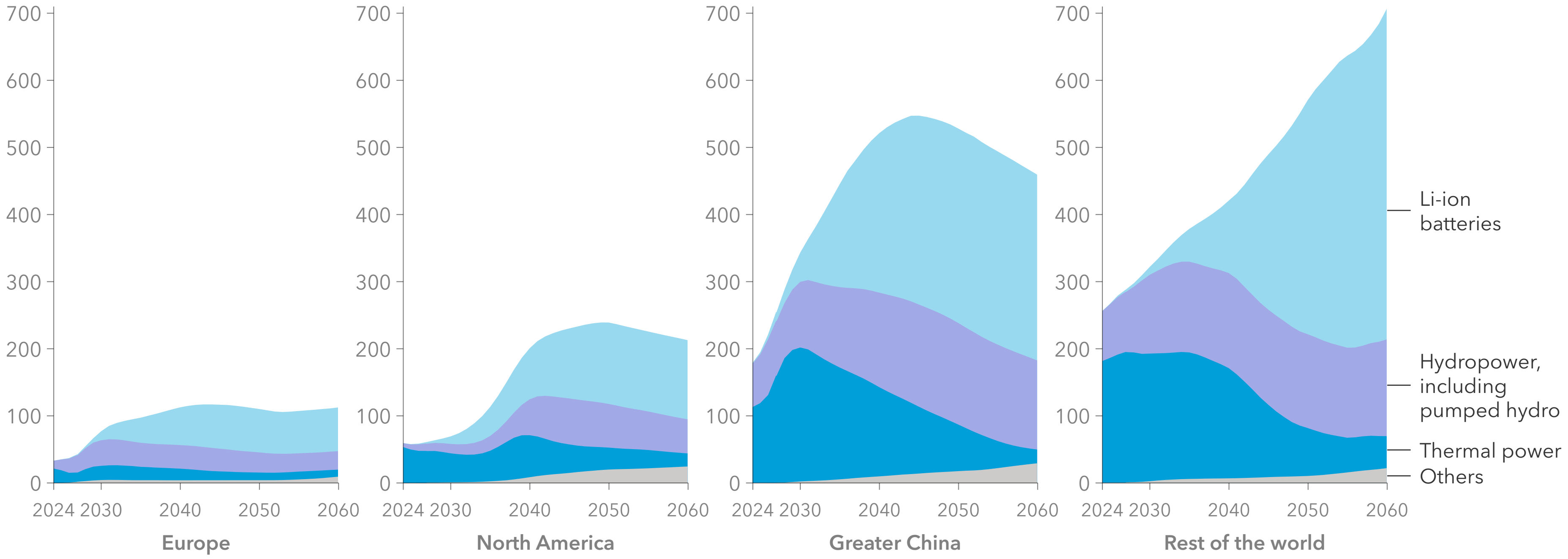


FIGURE 3.28 | Others includes power-to-hydrogen, nuclear, and long-duration storage; Li-ion batteries include utility-scale, distributed BTM, and EV V2G batteries.

4 HARD TO DECARBONIZE SECTORS

4.0 THE CHALLENGES FOR ELECTRIFICATION

High temperature

Achieving the high temperatures required for heavy industrial processes is a significant challenge for electrification. These processes demand a consistent and massive supply of heat, often exceeding 1000°C, which can be difficult and expensive to achieve with electricity. Several decarbonization alternatives will develop:

Bioenergy is projected to supply around 20% of industrial heat demand by 2060, though sourcing sustainable, high-quality biomass at scale is a limiting factor.

Carbon capture and storage (CCS) on fossil-fuel installations for industrial heat is forecast to capture 500 Mt of CO_2 annually by 2060.

Hydrogen, either burned alone or blended with natural gas, is expected to account for 6% of the energy mix for industrial heat, making it a limited long-term solution.

High energy density

Sectors like aviation, maritime shipping, and long-haul trucking require energy-dense fuels for long-distance travel. Fossil fuels provide a level of energy density that current and expected battery technologies cannot match. Alternative liquid and gaseous fuels will emerge:

Biofuels, such as sustainable aviation fuel (SAF), will grow in the near term and are expected to constitute around 25% of the maritime and aviation fuel mix by 2060.

In the long term, **hydrogen and its derivatives**, like ammonia, will be critical. They are projected to power 10% to 35% of hard to electrify sectors such as aviation and maritime by 2060.

The concept of **onboard carbon capture** is also being explored in shipping, and is forecast to capture 100 Mt of CO_2 annually by 2060.

Chemical processes

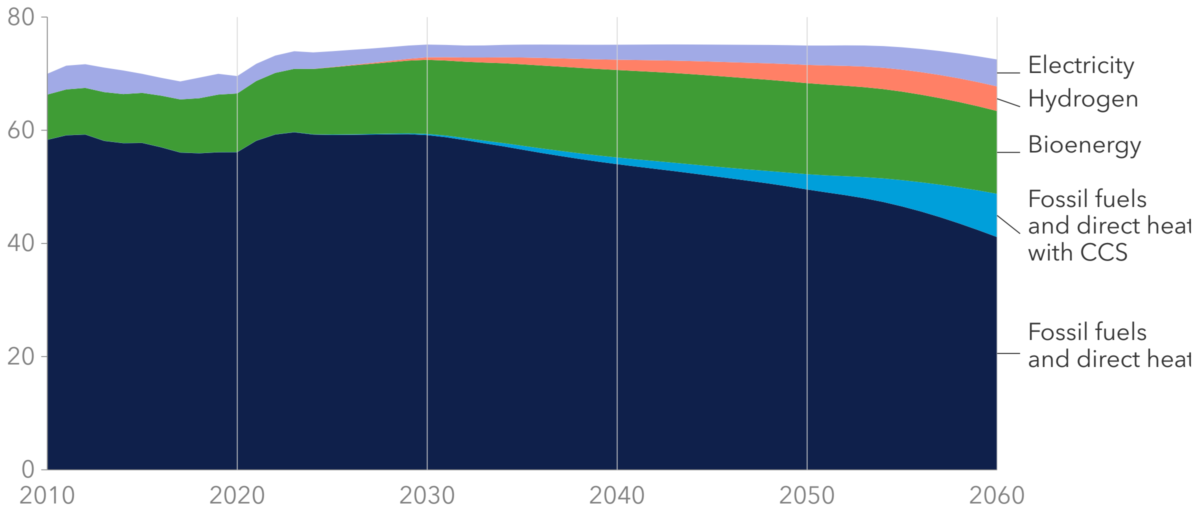
Decarbonizing some industries requires addressing 'process emissions', where CO_2 is released from chemical reactions, not just fuel combustion:

In **cement production**, on top of fossil fuel emissions, heating limestone releases CO_2, making CCS essential. CCS is forecast to capture 8% of total annual emissions by 2060.

In **iron and steel** manufacturing, coal-derived coke is a chemical reductant. The industry is shifting to hydrogen as a clean alternative, with around 30% of primary steel expected to be made this way by 2060.

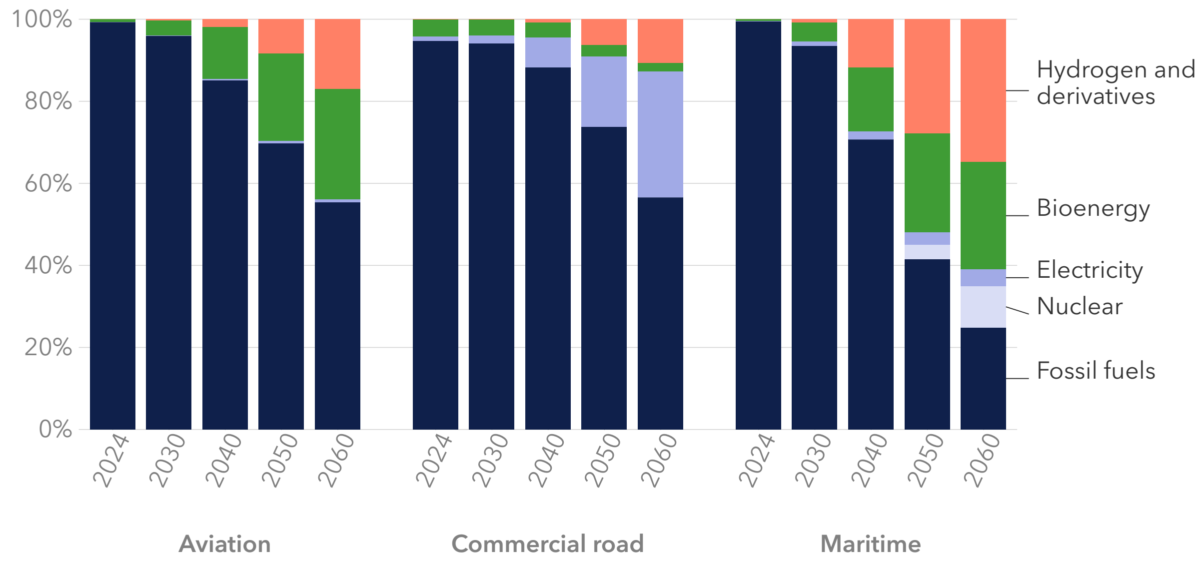
Producing **ammonia for fertilizers** from coal or natural gas creates process emissions. 'Green ammonia' (using hydrogen from renewables) and 'blue ammonia' (using CCS) are forecast to account for 22% and 26% of total production by 2060, respectively. providing partially decarbonized food security.

Industrial heat energy demand (EJ/yr)

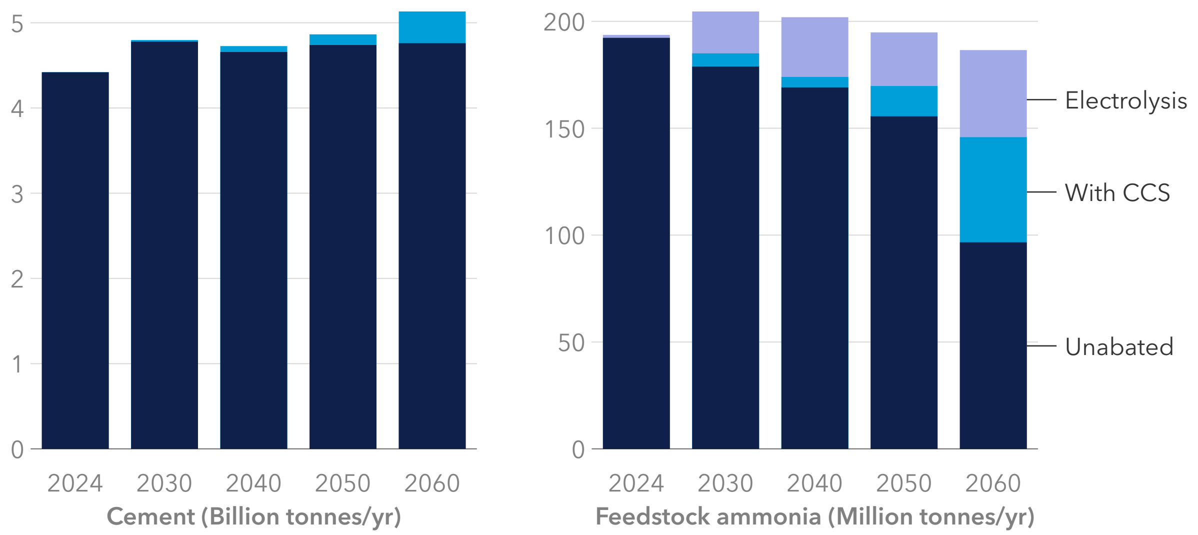


Historical data source: IEA WEB (2025), DNV analysis

Share in final energy demand by energy carrier, selected transport subsectors



World production of key commodities



4.1 HYDROGEN HIGHLIGHTS

Delayed uptake

- Future demand for renewable and low-carbon hydrogen and its derivatives – ammonia, e-methanol, and other e-fuels – as energy carriers will grow from current negligible levels to surpass 6 MtH_2/yr by 2030, 165 MtH_2/yr by 2050, and 260 MtH_2/yr by 2060.
- Renewable and low-carbon hydrogen are essential for lowering emissions in energy-intensive sectors that are difficult to electrify. To align with the goals set by the *Paris Agreement*, hydrogen and its derivatives must account for about 15% of the world's energy demand by 2050 (DNV, 2023).
- We forecast global uptake of hydrogen to fall far short of these goals: 0.15% of the global final energy mix by 2030, around 4% by 2050, and close to 6% by 2060.
- National strategies and policies support hydrogen, but implementation delays, insufficient demand-creation policies, delayed updates to standards for large-scale production and storage, and insufficient transparency in the value chain continue to hinder progress and delay uptake in 2030s.

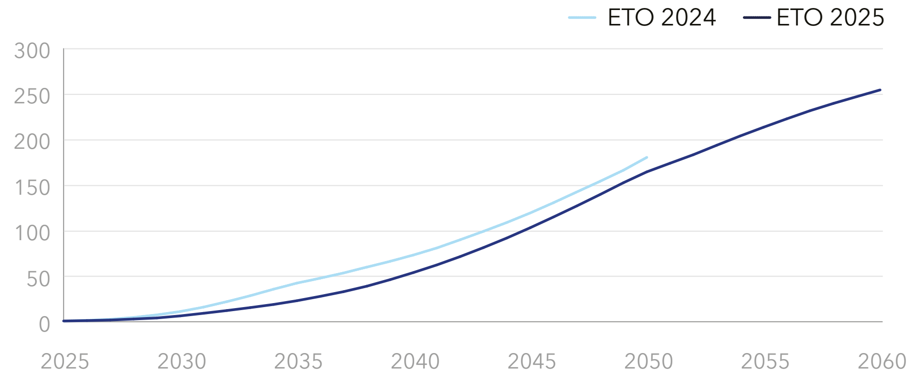
Demand driven by frontrunners in hydrogen use

- The predominant applications of hydrogen will be in transport and manufacturing – each accounting for 44% of global energy demand – followed by buildings at 9%.
- High-income regions are pioneering hydrogen energy technology developments and uptake through energy and industrial policies. Policy developments in Europe and OECD Pacific are leading to a growing number of projects and imports (see Chapter 6 for further details). As a result, we expect these regions to achieve significantly higher shares of hydrogen and its derivatives in their final energy mixes, positioning them as frontrunners in hydrogen use.
- We project OECD Pacific to lead in hydrogen adoption, reaching 8% of its energy mix by 2050 and 12% by 2060. Europe will follow with 7% by 2050 and 9% by 2060, while North America will grow to slightly over 4% in 2050 and 8% by 2060.

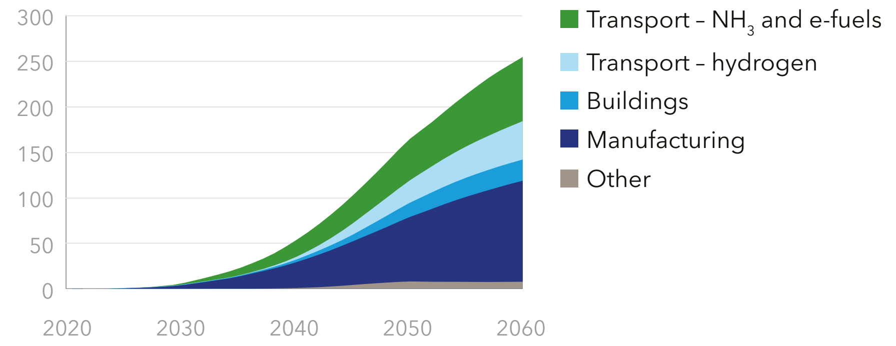
Electrolysis-based production will dominate in the long run

- By 2030, the leading producers of hydrogen as an energy carrier will be North America (34% of global production), China (20%), Europe (15%), and the OECD Pacific (15%). Beyond 2030, we foresee the Middle East and North Africa region ramping up production, reaching 18% of the global total by 2040.
- Hydrogen from steam methane reforming with carbon capture and storage (CCS) will dominate until 2040 in most regions (except the OECD Pacific). Later, falling costs will lead to electrolysis supplying over half of North America's hydrogen and around 75% of Europe's by 2060. Both the OECD Pacific and China will be producing hydrogen for energy purposes entirely based on electrolysis by end of the forecast period.
- The Middle East and North Africa will be the only top producing region that retains a substantial (75%) share of low-carbon fossil-based hydrogen by 2060 due to the abundance of cheap natural gas.

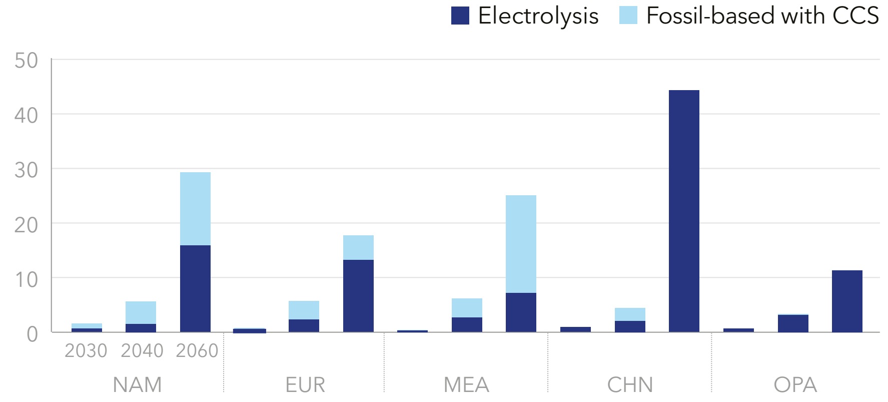
Reduced estimates for global demand for hydrogen as an energy carrier (MtH_2/yr)



Global demand for hydrogen as an energy carrier by sector (MtH_2/yr)



Hydrogen supply by production routes in top producing regions (MtH_2/yr)



Hydrogen demand

Transport

Maritime
Renewable and low-carbon hydrogen derivatives will be central to decarbonizing international shipping. EU measures are already reshaping the sector: the *Emissions Trading System* (ETS) has applied to large ships since January 2024, with full allowance surrender from 2027, and *FuelEU Maritime* introduces penalties for not meeting well-to-wake GHG requirements from January 2025. Globally, the International Maritime Organization's (IMO) updated GHG Strategy – reinforced in 2025 with new emissions caps and carbon-pricing plans – is adding further pressure to adopt zero- or near-zero- GHG fuels and technologies. These policies are boosting demand for hydrogen derivatives, but large-scale uptake will hinge on lower production costs, robust lifecycle emissions verification, and expanded port infrastructure (see DNV *Maritime Forecast to 2050* (2025) for further details).

Electrification will remain limited to shore power at berth and short-range operations such as ferries. This leaves hydrogen-based fuels – notably ammonia and e-fuels – as the dominant zero-emission options by 2060. We project e-fuels, mainly e-methanol, to account for 100 PJ (1% of the fuel mix) by 2030, 800 PJ (6%) by 2040, and 1,500 PJ (14%) by 2060.

Ammonia, while costlier to produce, can use much of the existing infrastructure and benefits from relatively simple CO_2 capture when made from natural gas. This makes low-carbon ammonia the leading candidate in our long-term forecast, surpassing e-methanol in the overall fuel mix, at 21% and 14% respectively. We expect toxicity concerns will be resolved, enabling large-scale trade from low-cost production regions to global bunkering hubs. We forecast uptake at 10 PJ (0.1%) by 2030, 700 PJ (5%) by 2040, and 2,300 PJ (21%) by 2060, with faster growth in later decades as biogenic CO_2 for e-methanol becomes harder to source. While significant, these volumes fall short of the IMO's decarbonization pathway (see the discussion of maritime transport in Section 2.6 for further details). Although ammonia combustion is carbon-free, it produces nitrogen oxide (NO_x) emissions which contributes to air pollution and causes significant environmental and health impacts. However, this can be effectively mitigated through advanced engine and emissions-control technologies.

Aviation
We expect lower costs and strong policy mandates to drive hydrogen e-fuels in aviation during the 2030s. Since January 2025, the EU's *ReFuelEU Aviation* rules require 2% sustainable aviation fuel (SAF) in jet fuel – rising to 6% by 2030 and 70% by 2050 – of which e-fuels must account for at least 1.2% by 2030 and 35% by 2050. However, e-fuels are about four to five times more expensive than fossil kerosene, so their widespread adoption will depend on a significant increase in renewable electricity production to bridge the current cost gap.

By 2060, we project hydrogen-based e-fuels to outpace pure hydrogen by roughly three to one, supplying 13% of aviation's fuel mix. E-fuels have the advantage of being drop-in replacements compatible with all flight types, whereas pure hydrogen is best suited to short- and medium-haul routes due to its lower energy density and bulky storage needs that increase per-passenger costs. While liquid hydrogen could eventually power long-haul jet turbines, this would require redesigned fuselages to accommodate larger fuel volumes. In total, we expect pure hydrogen and e-fuels to provide about 17% of aviation energy use by 2060.

Road transport
In road transport, fuel cell electric vehicles (FCEVs) remain far less efficient, more complex, and costlier than battery electric vehicles (BEVs). Automakers are therefore prioritizing BEVs for passenger cars, a shift that will give BEVs a 99% share of new global passenger vehicle sales by 2060, with FCEVs at just 0.4%. While hydrogen was once seen as the front-runner for decarbonizing heavy trucking, battery-electric solutions are now gaining ground. Despite the development of hydrogen combustion engines, hydrogen's role will likely be limited to mostly heavy-duty and long-haul applications as a range extender. By 2060, hydrogen will supply about 5% of road transport energy – roughly 3,700 PJ, or 31 MtH_2 per year – more than biomass and natural gas combined.

E-fuels dominate aviation, while ammonia dominates maritime
World aviation and maritime subsectors demand for hydrogen and its derivatives (EJ/yr)

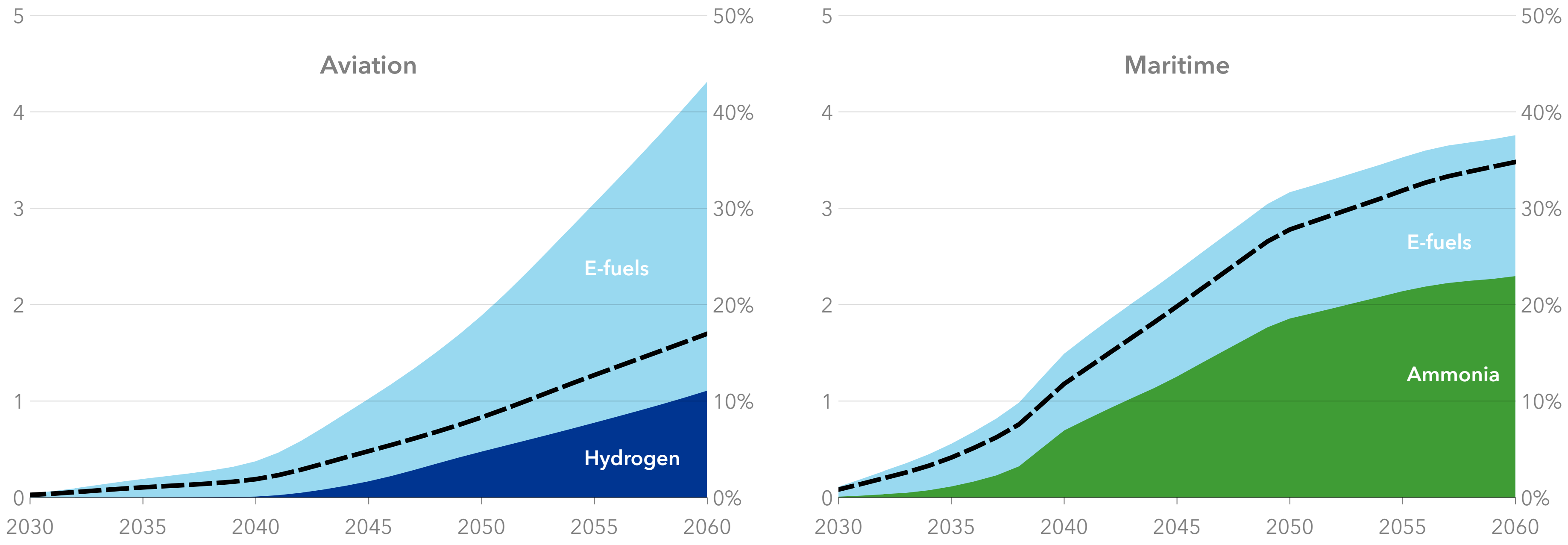


FIGURE 4.1 | Dotted line shows the share of hydrogen and its derivatives in energy demand (right axis).

Manufacturing

Hydrogen holds promise for replacing fossil fuels in industrial high-heat applications. However, deployment remains modest due to its cost making it less competitive than traditional fossil-fuel technologies. Competition is also emerging from technical advances in the electrification of industrial heat. The steel sector's pivot toward electric arc furnaces (EAFs) – which now account for 93% of planned new capacity (Armbruster et al., 2024) – signals a strong shift away from conventional blast furnace processes. In direct reduction of iron (DRI) processes, industries will be able to use unabated fossil-based hydrogen – even in newly built plants – postponing the shift to renewable and low-carbon hydrogen until it becomes cost-competitive, even when factoring in emission costs.

Still, we anticipate renewable and low-carbon hydrogen to play a significant role in the manufacturing sector by 2060, particularly in regions leading the transition: Greater China (27% of hydrogen demand in the sector), North America (25%), and Europe (15%). We forecast the demand for hydrogen as an energy carrier in manufacturing will experience gradual growth, reaching nearly 13 EJ/yr (approximately 110 MtH_2/yr) by 2060 (Figure 4.2). This accounts for about 9% of the total energy demand in manufacturing. Notably, the iron and steel industry will represent the largest portion of hydrogen demand in manufacturing, amounting to 8 EJ/yr (62% of the total). This is in addition to the non-energy use of hydrogen in DRI, which will be approximately 1.3 EJ/yr, equivalent to around 11 MtH_2/yr.

Iron and steel drives hydrogen adoption in manufacturing

World hydrogen demand in manufacturing (MtH_2/yr)

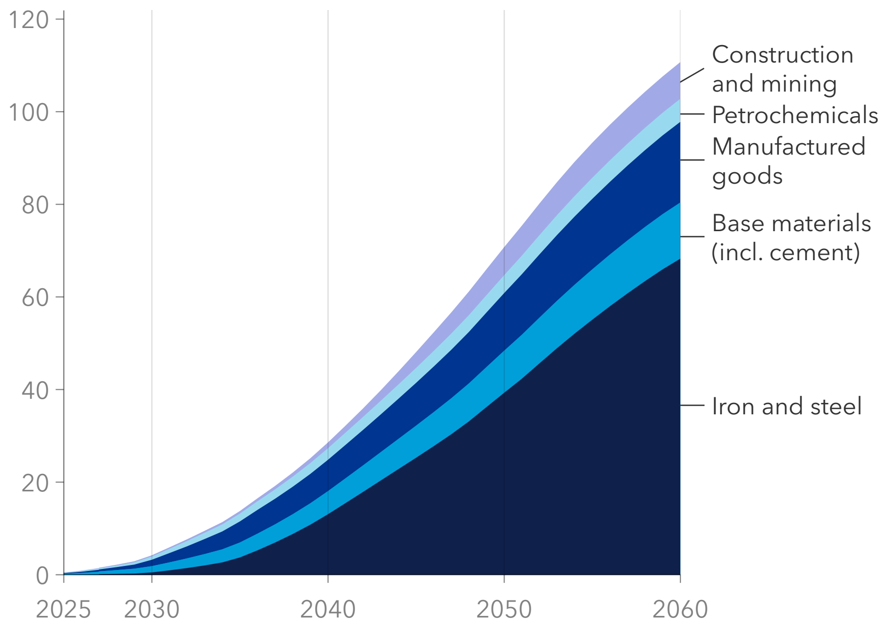


FIGURE 4.2 |

85% of world hydrogen from low-carbon origin by 2060

World hydrogen production by production route (MtH_2/yr)

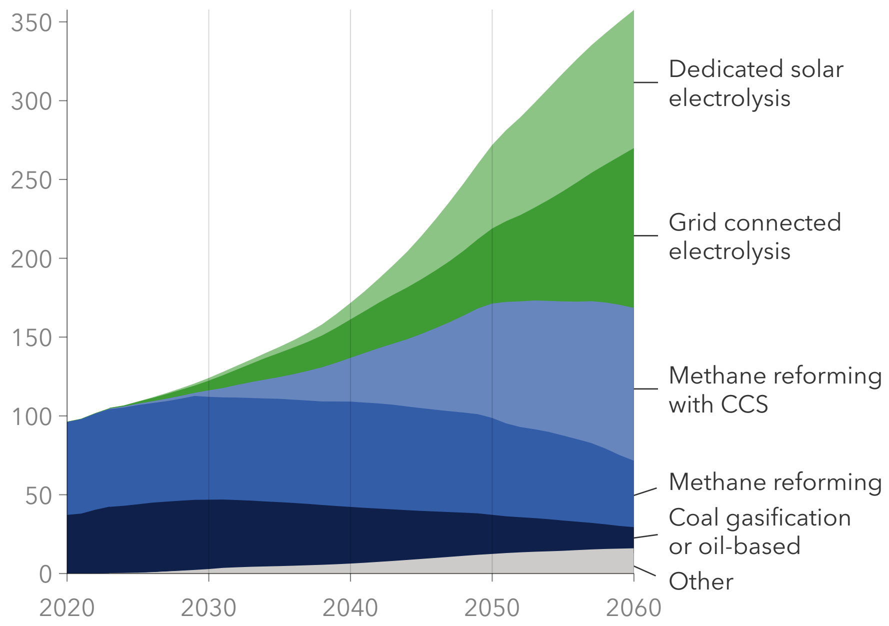


FIGURE 4.3 | Historical data source: Future of Hydrogen (IEA, 2019), Global Hydrogen Review (IEA, 2021)

Buildings

We project hydrogen use in buildings to reach around 3 EJ/yr (23 MtH_2/yr) by 2060, just 1.6% of sector energy demand. This is a fraction of natural gas, which we expect to supply about 20% of building energy needs. Most of this hydrogen will be utilized for water heating (56%) and space heating (25%). Uptake will be lower than alternatives like electric heat pumps and district heating due to lower efficiency, higher costs, safety concerns, and infrastructure constraints. We anticipate hydrogen utilization in buildings to be concentrated in North America (44%), Europe (22%), and the OECD Pacific (15%), where natural gas networks already exist and hydrogen supply is more accessible.

Power and seasonal storage

In regions rich in solar and wind, hydrogen can help manage peak demand and store surplus electricity over long periods, though with high energy losses and significant storage needs. Re-electrification will remain a lower-priority use, with hydrogen entering power generation from around 2030, initially blended with natural gas. The OECD Pacific will lead adoption, followed by Europe, Greater China, and later North America in the mid-2040s. Even by 2060, hydrogen for power generation will remain limited at just 1.4 MtH_2/yr, or less than 1% of total hydrogen demand.

Hydrogen as feedstock

Currently, hydrogen is essential for two primary applications: oil refining and ammonia production for fertilizers. Our forecast indicates that while the total demand for hydrogen in these sectors may slightly decrease due to minor demand decreases in respective sectors, there will be an increasing need for hydrogen derivatives used in energy applications. By 2055, we expect demand for hydrogen (produced via conventional fossil and low-carbon routes) to produce e-fuels and as a fuel source for ammonia to surpass the combined demand for hydrogen in oil refining and fertilizer production.

Hydrogen supply

Future hydrogen supply will be shaped by two interlinked forces: the rising demand for hydrogen as an energy carrier and the shift toward cleaner production methods. By 2030, we project that 12% of global hydrogen will come from low-carbon and renewable sources. Methane reforming with CCS will contribute 14% of total supply, while electrolysis will account for 8%.

By 2060, the transformation will be dramatic: 85% of the world's hydrogen will originate from low-carbon or renewables. This will include 27% from methane reforming with CCS, 28% from grid-connected electrolysis, 25% from solar-powered electrolysis, 3% from wind-powered electrolysis, and 1% from nuclear-powered electrolysis (Figure 4.3).

Low-carbon hydrogen: Currently, the cheapest low-carbon option is methane reforming with CCS (blue hydrogen) averaging about USD 2/kgH_2 in regions with low gas prices, such as North America and North East Eurasia. In gas-importing regions like Europe, costs exceed USD 7/kgH_2, though we expect prices to fall by the 2030s. CCS faces challenges: reliance on gas prices, technology maturity, long-term storage issues, cost uncertainties, and slow scaling. Achieving capture rates above 90% is still uneconomical, limiting competitiveness against renewables-based hydrogen in the longer term. Even so, we expect falling reforming and CCS costs combined with higher carbon prices will boost adoption, particularly for ammonia production. By 2060, methane reforming with CCS will supply 97 MtH_2/yr, 27% of global hydrogen production.

Renewable hydrogen: Hydrogen from dedicated renewables-based electrolysis currently costs around USD 6/kgH_2 or more – far more than unabated fossil-based production. We project costs will fall by roughly 30% by 2030, with solar- or wind-powered electrolysis reaching about USD 4/kgH_2, and further to an average of around USD 3/kgH_2 by 2050, with some projects dropping below USD 1/kgH_2. Still, dedicated solar PV electrolysis achieves cost parity with methane reforming plus CCS only by the end of the forecast period (Figure 4.4). These declines are driven by technology learning rates, lower CAPEX, reduced financing risk, streamlined project costs, and higher annual operating hours, which vary by technology and region.

For grid-connected electrolysers, electricity costs dominate, making affordable power essential. While greater variable renewable energy integration will create more hours of very low- or zero-cost electricity, this impact will be modest before 2030; near-term cost reductions will rely mainly on falling capital costs and government support.

Key hydrogen-supporting regions – Europe, and OECD Pacific – are tightening electricity sourcing and emissions standards. Japan sets separate rules for low-carbon hydrogen and ammonia, South Korea links support to a four-tier emissions scale, Canada's tax credits vary by lifecycle GHG intensity, and the EU requires renewable fuels of non-biological origin to deliver at least 70% GHG savings over fossil hydrogen. From 2028, EU rules will require 'additionality', ensuring renewable electricity for hydrogen comes from new capacity, and will introduce 'temporal matching' (hourly alignment of renewable supply and hydrogen production) to prevent competition with existing renewable demand.

Hydrogen transport

Gaseous low-to-medium pressure hydrogen will mainly be moved by pipelines over medium distances within and between countries, but intercontinental transport will be rare. Ammonia will dominate long-distance trade with 52% transported because it is safer and more convenient for shipping (Figure 4.5). We expect more than half of global hydrogen pipelines will be repurposed from natural gas infrastructure – up to 80% in some regions – as repurposing costs only 10 to 35% of building new lines.

Pipelines are most cost-effective for large volumes over medium distances, while trucking and rail (often using ammonia) suit shorter routes. Seaborne hydrogen transport, entirely in the form of liquid ammonia in our forecast, is viable for long distances but costly, adding USD 1.5–2/kgH_2 due to liquefaction and regasification. By 2060, 3% of hydrogen will be transported by ship and 6% via interregional pipelines.

Global seaborne ammonia trade will expand seven-fold between 2030 and 2060, growing from negligible volumes in the mid-2030s to 65 Mt/yr (74% of total hydrogen and derivatives trade) by 2060.

Electrolysis will eventually reach cost parity with low-carbon production route

Levelized cost of hydrogen by cost components, Europe (USD/kgH_2)

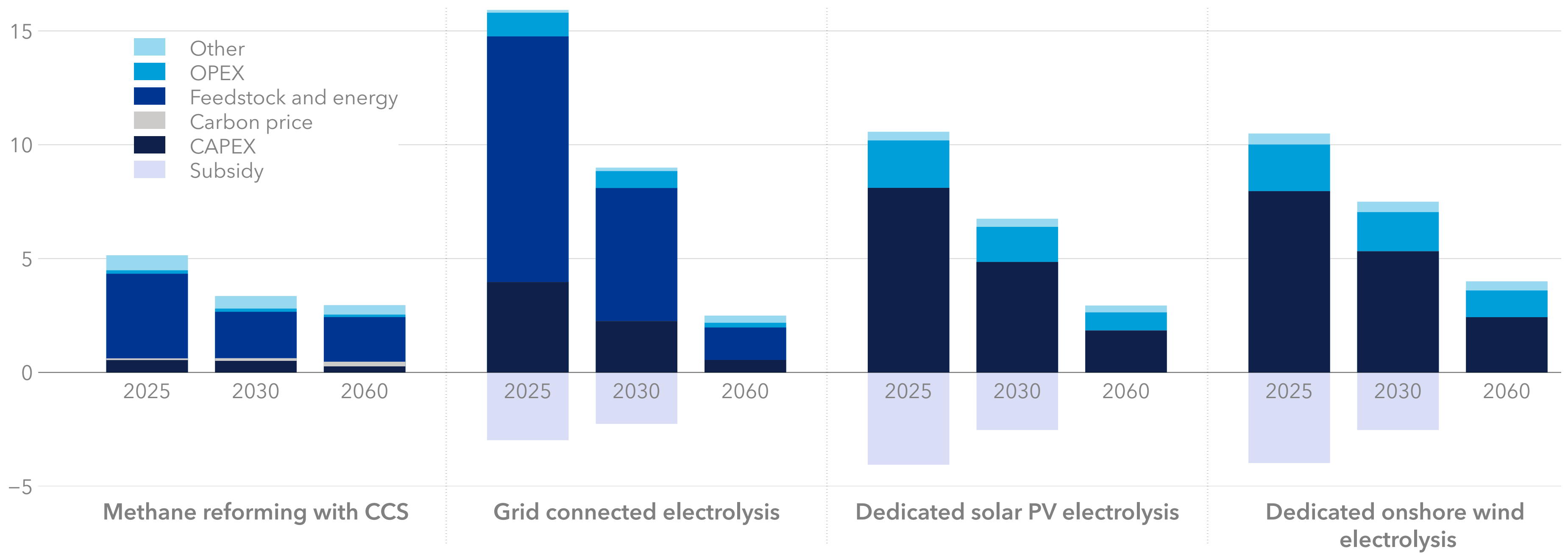


FIGURE 4.4 |

Ammonia will lead long-distance hydrogen trade

Transport of hydrogen and ammonia (Mt/yr)

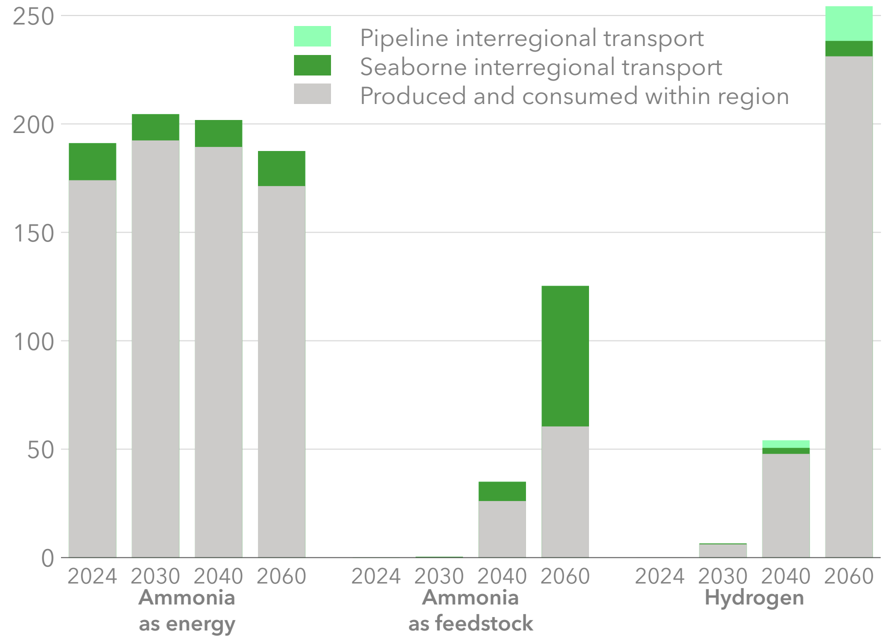


FIGURE 4.5 | Hydrogen within region will be transported in gas form; seaborne hydrogen transport will be entirely in the form liquid ammonia.

4.2 CCS

- **The turning point for CCS has arrived, with capture and storage capacity expected to quadruple by 2030.**
- **After 2030, growth in hard-to-decarbonize sectors will accelerate, with CCS deployment in manufacturing rising nearly ten-fold and making up about 25%* of all captured emissions by mid-century.**
- **CCS will grow to capture 6% of global CO_2 emissions in 2050, falling significantly short of what is required for any net-zero outcome.**
- **Carbon dioxide removal (CDR) will capture 610 $MtCO_2$* in 2050 – 38% of total captured emissions.**

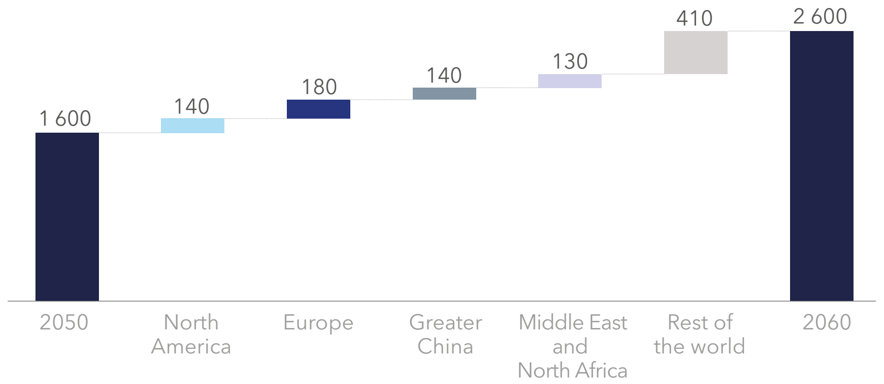
For further information, please refer to our recent *Energy Transition Outlook: CCS to 2050.* While the CCS report focuses largely on the short term and up to 2050, most of the remainder of this page concentrates on the longer term, extending to 2060.

*This number has been updated since the publication of the CCS report following an update to the ETO model. The updates are driven by, among other things, recent policy developments, especially the EU being more explicit about including domestic and international CDR to meet 2040 climate targets (Obienu, 2025).

CCS will continue growing beyond mid-century and capture 16% of global CO_2 emissions in 2060.

- We forecast that 1,600 $MtCO_2$/yr will be captured and stored by mid-century. This includes volumes from point sources, and direct air capture (DAC).
- The leading regions in CCS will be Europe and North America (23% of global total each), followed by the Middle East and North Africa (11%) and Greater China (8%).
- In the 2050s, CCS will continue growing to increase by more than 60% to 2,600 $MtCO_2$/yr in 2060. The growth is spread out relatively evenly among the regions, with the leading regions accounting for around 60% of net capacity additions and the rest of the world accelerating capacity deployment in various sectors.

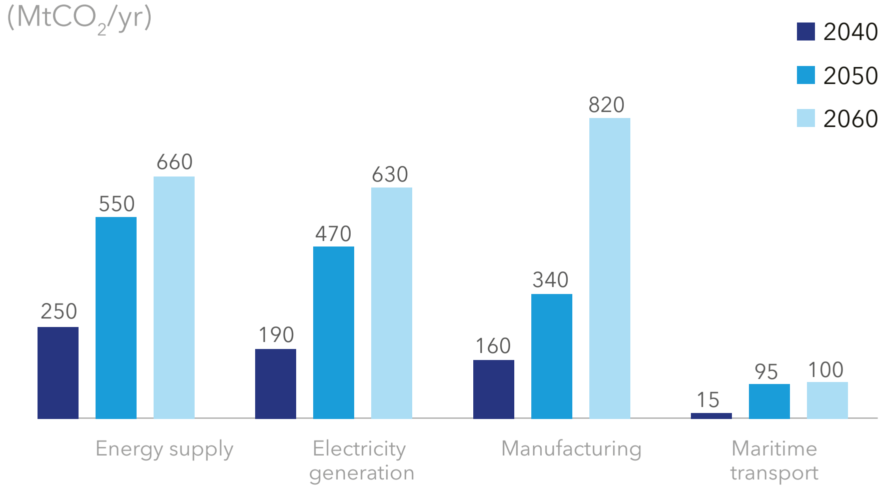
Additional emissions captured with CCS after 2050
($MtCO_2$/yr)



After 2040, the strongest growth will be in hard-to-decarbonize sectors, with manufacturing accounting for almost 40% of annual CO_2 captured in 2060.

- CCS is essential to address hard-to-decarbonize emissions from manufacturing sectors, like steel production, and from maritime transport, where we expect onboard capture to scale from the 2040s in parts of the global shipping fleet. Manufacturing sectors will be the biggest users of CCS in Europe.
- CCS in power will also see substantial growth from 2040 to 2060, reaching close to 30% of total CO_2 captured. However, the majority of CCS in power will come from biomass in Europe and North America. Capturing CO_2 from fossil fuels, predominantly coal, will be most prominent in China.
- CCS in energy supply sectors will show less rapid growth and will be driven by production of hydrogen and ammonia in North America and the Middle East and North Africa. By 2060, this sector will still account for a significant 30% of total emissions captured globally.

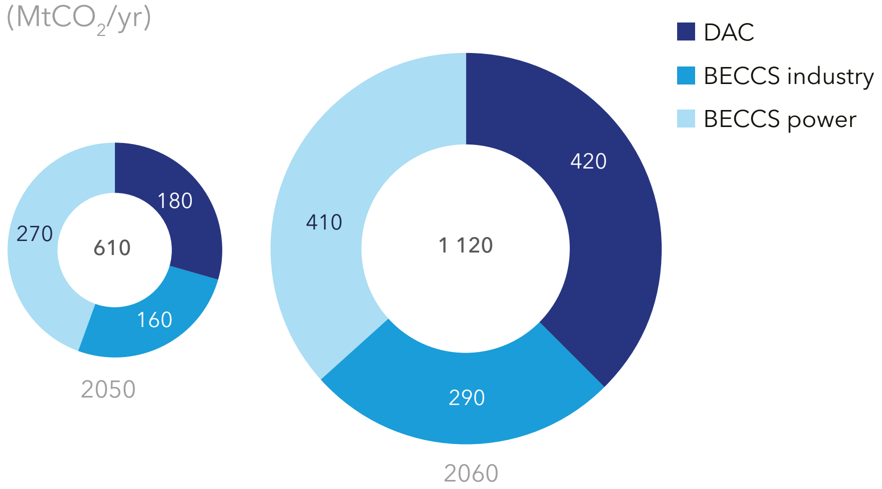
CCS deployment across sectors
($MtCO_2$/yr)



After 2050, carbon dioxide removal (CDR) will continue growing and reach 1,100 $MtCO_2$/yr by 2060.

- As global emissions continue to accumulate, CDR becomes important in the second half of the century to reduce the large carbon budget overshoot. By 2060, CDR will capture 42% of total CO_2 emissions captured and stored.
- Bioenergy with CCS (BECCS) is generally the cheaper CDR option and will be used primarily in renewable biomass for power and manufacturing. By 2060, 62% of CDR will come from BECCS, with more than half of that applied in power.
- DAC costs remain higher, just slightly below USD 350/tCO_2 even by 2060, but voluntary and compliance carbon markets still ensure the capture of 420 $MtCO_2$/yr by the end of our forecast period.

Carbon dioxide removal in 2050 and 2060 by sector
($MtCO_2$/yr)



4.3 BIOENERGY

Bioenergy is currently the largest renewable source of primary energy supply and will remain so until 2040.

Bioenergy will see slow but steady growth in total supply from 57 EJ/yr today up to 77 EJ/yr in 2050, and will continue to meet 9% of global energy demand in 2060. Bioenergy demand is currently dominated by inefficient traditional biomass, but the shift to modern bioenergy will drive the majority of growth toward 2050.

Modern bioenergy on the rise

Today, bioenergy demand is dominated by traditional biomass – using biomass in its raw or minimally processed form – typically for cooking and heating in low-income regions. However, this will decline, and more efficient modern bioenergy will see strong growth in transport, manufacturing, and power.

Biomass is a versatile energy source that can be converted into high-quality fuels and gas with low or no emissions. Biogases can meet the high-temperature needs of manufacturing where low-emission alternatives are scarce, and as such are increasingly replacing natural gas in hard-to-decarbonize industries such as cement and metal production. Production of biomethane, the most widely used biogas in industry, is growing and will meet 10% of bioenergy demand in 2060. The highest shares of biomethane occur in Europe (15%) and OECD Pacific (18%).

The regulatory regime in aviation (especially in North America, Greater China, and Europe) is facilitating a growing market for SAF. Biomass will provide liquid biofuels for SAF equalling 7 EJ/yr by 2060, twice as much as provided by e-fuels (including hydrogen). Nevertheless, oil will retain the lion's share (55%) of energy supply in the sector.

Biofuel is already used in maritime transport by blending biofuels with fossil. Its use will grow steadily from a very low volume to reach a 5% share in 2030. By 2060 bioenergy will be the biggest non-fossil energy source in the sector, supplying 26% (3 EJ/yr) of total maritime demand. At this level, it surpasses the remaining use of fossil fuels (25%).

Electricity to the grid from biomass will grow by more than 50% from today to 2060. The share of BECCS will grow continuously through the period, from 3% of biomass electricity in 2030 to 37% in 2060. This means that all net growth by 2060 will be provided from BECCS. Electricity from biomass will peak in 2050 and will provide below 2% of the global total electricity demand in 2060 after strong growth of other renewables.

Stubborn pockets of traditional bioenergy

Currently, buildings is bioenergy's largest demand sector. Bioenergy use in buildings will reduce by 25% globally by 2060, driven by electricity replacing the biomass combustion for space and water heating and cooking. Sub-Saharan Africa is the exception where we see growing demand for traditional biomass (from 6 EJ/yr to 9 EJ/yr) despite strong international initiatives to phase out traditional cookstoves. These cookstoves badly impair human health and the environment and perpetuate social inequalities as the onus of cooking and sourcing the energy typically falls on women and girls. The growing demand in this region is due to a combination of continued population growth and reduced GDP growth in the region that limits the ability to finance a transition away from the traditional stoves.

Sustainability concerns

The technical potential for bioenergy is 97 to 147 EJ (IRENA, 2020), of which 40% is from agricultural residues, 30% forestry residues, 25% energy crops, and 5% municipal/industrial waste. The sustainable part of the technical potential is not explicitly quantified. With our projected global consumption levels surpassing 70 EJ/yr, there will be cases of sustainability conflicts, typically with regard to desertification and energy crops. Energy crops – such as corn, sugarcane, soybeans, and rapeseed – could displace food crops or natural ecosystems when not grown on marginal or degraded land. This concerns most regions and is increasingly important as we project demand for modern bioenergy will grow. Further work is needed to quantify the potential for sustainable bioenergy based on updated (stricter) sustainability requirements appearing, for example the EU's *Renewable Energy Directive* (RED II).

Modern bioenergy drives uptake

World bioenergy demand (EJ/yr)

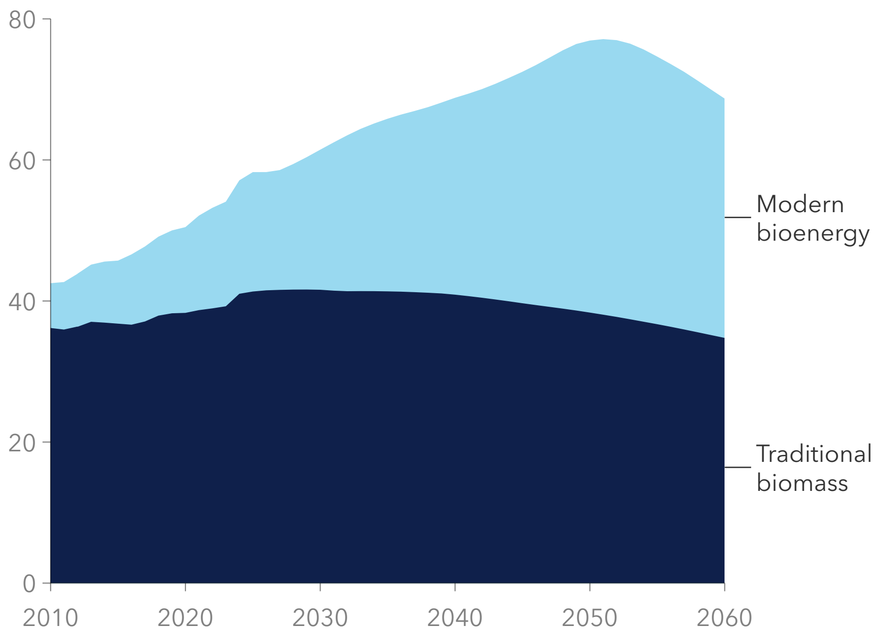


FIGURE 4.6 | Historical data source: IEA WEB (2025)

Aviation overtakes road as electrification progresses

World bioenergy demand in selected sectors (EJ/yr)

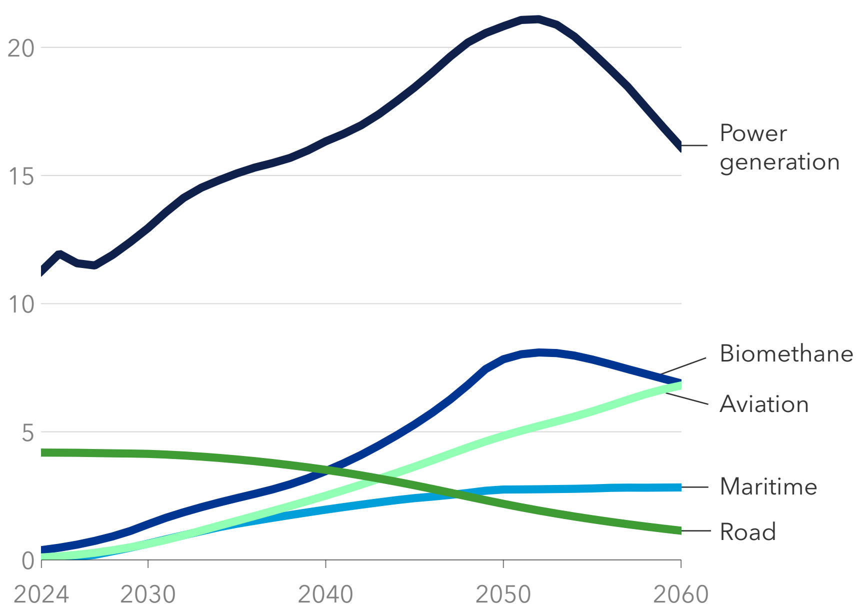


FIGURE 4.7 | Historical data source: IEA WEB (2025)

4.4 DIRECT HEAT

Direct heat supplies 6% of energy demand from both manufacturing and buildings at 9 and 8 EJ/yr, respectively. By 2060, we forecast manufacturing direct heat demand will decline to 8 EJ/yr, while district heating network expansion increases building sector demand to 9.5 EJ/yr.

Current state and future expansion

Steam-based district heating became widely implemented in North East Eurasia and Europe in the 20th century thanks to mandated district heating connections, state or municipal ownership of infrastructure, and regulated heat prices. Today, district heating is gaining renewed momentum for decarbonizing building space heating (Figure 4.8). Replacing individual boilers with centrally distributed heat from diverse, locally available heat sources eases grid constraints and improves energy efficiency. Today, direct heat supplies 41% of space heating in North East Eurasia and 13% in Europe; in China it supplies over 80% in the northern, colder half of the country (Yuan et al., 2024).

North East Eurasia focuses on maintaining and upgrading existing infrastructure, such as the Karaganda District Heating Network Rehabilitation project in Kazakhstan, rather than expansion (Asian Development Bank, 2017). Decarbonization is the primary goal of expanding district heating in Europe, where renewables and heat pumps now make up 52% of heat sources (Euroheat & Power, 2025). Bioenergy is the largest renewable heat source in European networks, followed by captured heat and geothermal.

In North America, deployment has been limited to densely clustered non-residential buildings like hospitals and business parks (EERE, 2020). We expect only 10% of residential space heating to be district heating by 2060 in North America despite finding that 40% of the population could viably be supplied with district heating (see fact box on how we calculate district heating demand). However, we expect the heat sources to be largely non-fossil, comprising 50% heat pumps and 33% renewables.

Global district heating connections are steadily growing

Households with district heating (Million households)

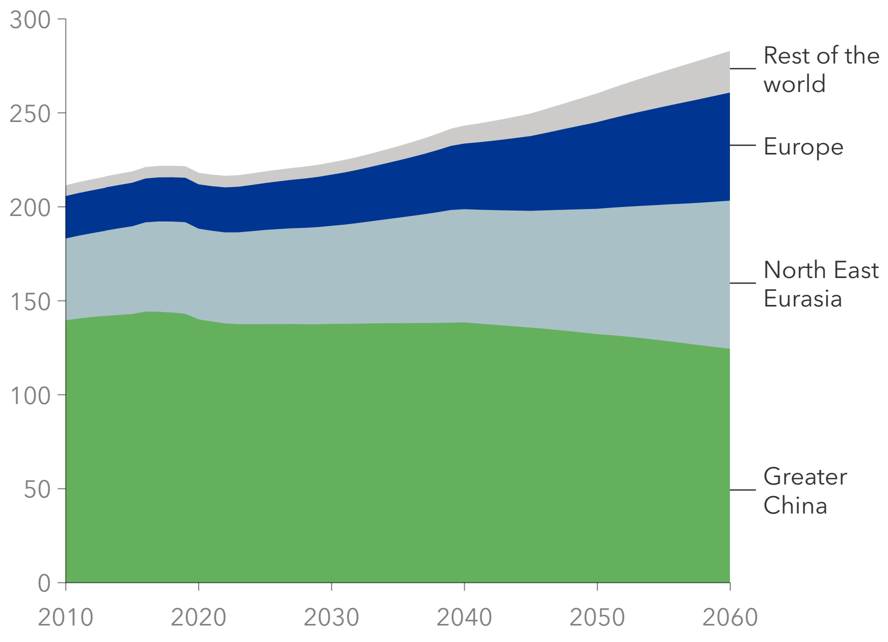


FIGURE 4.8 |

Heat pumps will be main source of district heating

Heat supply by source (EJ/yr)

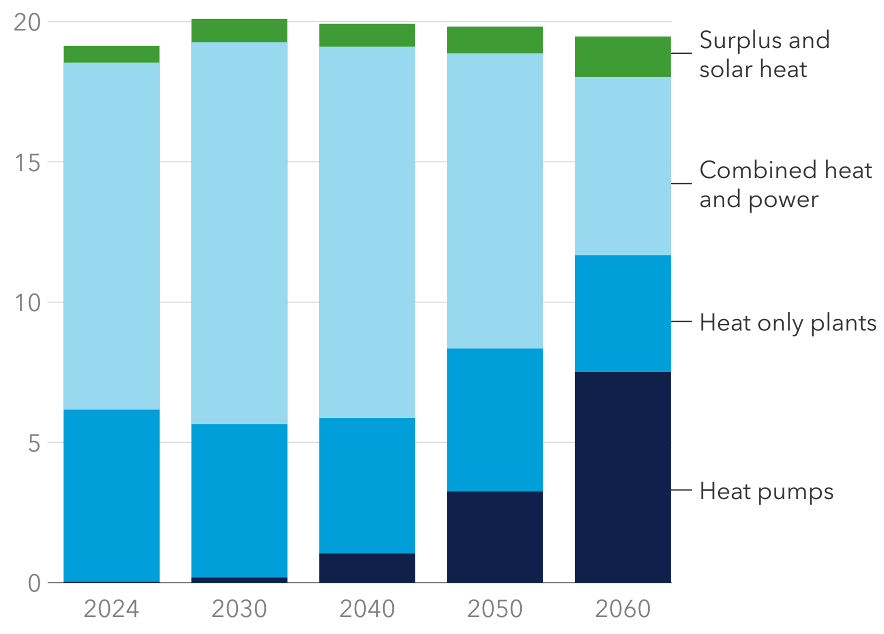


FIGURE 4.9 |

Diversification of heat source supplies

Cogeneration plants (CHP) and heat-only-plants (HOP) have provided steam to district heating since the 19th century (Kelly, 2016). Today, fossil fuels still supply nearly 90% of global direct heat demand. We forecast non-fossil sources to grow from 7% currently to 17% by 2060. Electrification through heat pumps will provide 38% of total direct heat demand, while fossil-based sources fall to 41% by 2060 (Figure 4.9). As Europe phases out fossil CHP plants to align with broader decarbonization goals, the region is turning to non-fossil alternatives like biomass, solar, and surplus heat from sources such as data centres (Energiforsk, 2024). Opportunities for heat storage such as in open air caverns, rocks, and even urban buildings are also being explored to minimize peak demand and seasonal variability.

How we calculate district heating demand

Direct heat provides thermal energy, through hot water or steam, from power stations and industrial processes to nearby consumers. District heating is most economically viable where high population density intersects with substantial heating demand, typically measured by heating degree days (HDD).

We conducted a GIS-based analysis of urban population densities and HDD. Analysing the intersection between the two factors, we calculated region-averaged heat demand density in GWh/(km²-yr) for regions with HDD over 1,500. With a baseline demand density threshold of 2.5 GWh/(km²-yr), we determined the fraction of the urban population that could viably be serviced with district heating.

The analysis does not account for proximity to heat sources and infrastructure, which would impact the feasibility. Moreover, policy plays a central role, especially where regulation supports long-term investment and coordinated planning such as promoting purpose-built pipe networks, as retrofitting is usually expensive and difficult. We applied regional policy factors which reflect our assessment of the fraction of the total potential likely to be realized through policy support.

5 THE EVOLVING FOSSIL FUEL ROLE

5.0 HIGHLIGHTS

The evolving fossil fuel role

Global energy in 2024 remained reliant on fossil fuels for 80% of total primary energy. Oil stood at 28% of primary energy, gas 26%, and coal 26%. Despite this dominance, renewables are now actively replacing them. This leads us to project a decline in fossil fuel consumption from 2026. The sheer scale of change will see fossil sources merely plateauing in the next few years and then declining in absolute terms only from the 2030s – a fast transition in historical terms, but slow from the perspective of climate goals.

The long goodbye

Coal demand plunges from 171 EJ in 2024 to 32 EJ by 2060 (only 5% of global primary energy by then). Oil stays flat near 180 EJ through to 2030, then drops to 86 EJ by 2060 (13% of primary energy). Gas demand rises from 169 EJ in 2024 to 190 EJ by 2035, plateaus until 2040, then falls to 131 EJ by 2060 (20% of primary energy). Through to 2060, the transition to renewables in the power generation mix is the largest driver of the decline of coal and natural gas (Figure 5.1). Oil use in transport shrinks from 113 EJ to 47 EJ due almost entirely to electrification. All fuels across other sectors (e.g. manufacturing) also decline, but less steeply – especially gas, which remains relatively stable around 114 EJ.

Non-energy use

Although fossil fuels decline in the overall energy mix, we expect them to maintain a strong presence in non-energy uses – holding steady at around 45 EJ through 2060. Currently, 14% of oil, 10% of gas, and 2% of coal are used as feedstock for plastics, petrochemicals, asphalt, and similar products. However, as fossil fuel use for energy falls, the relative share of non-energy applications will rise (see Section 5.4). Non-energy uses do not involve combustion and thus do not produce direct emissions.

Transport and power drive fossil fuel reduction

Energy demand by sector (EJ/yr)

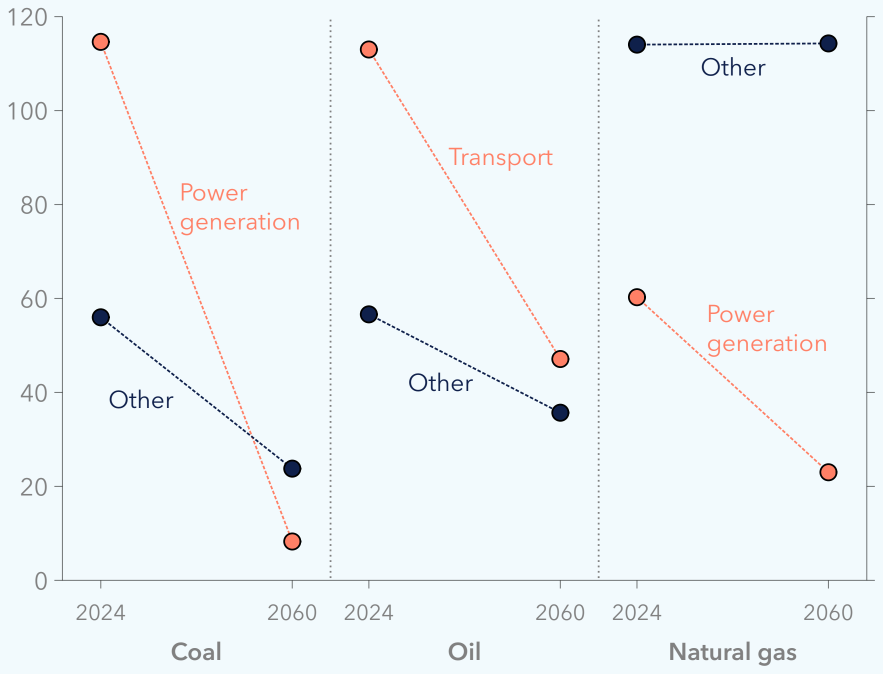
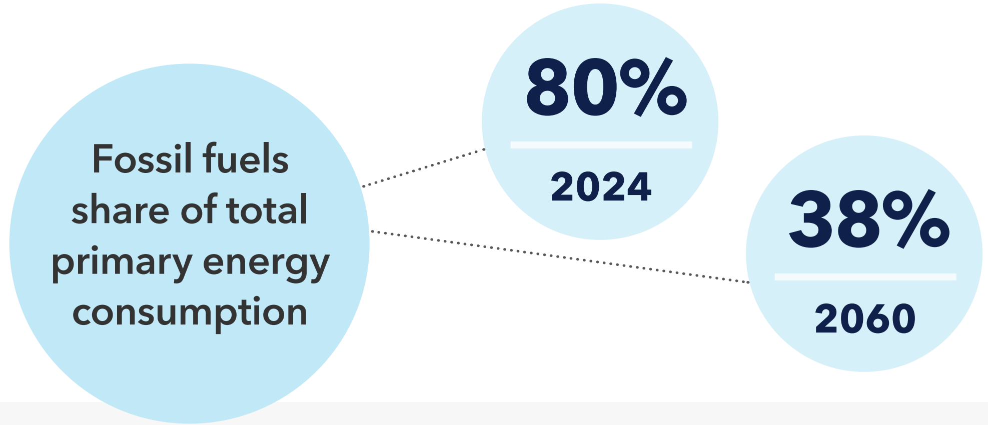
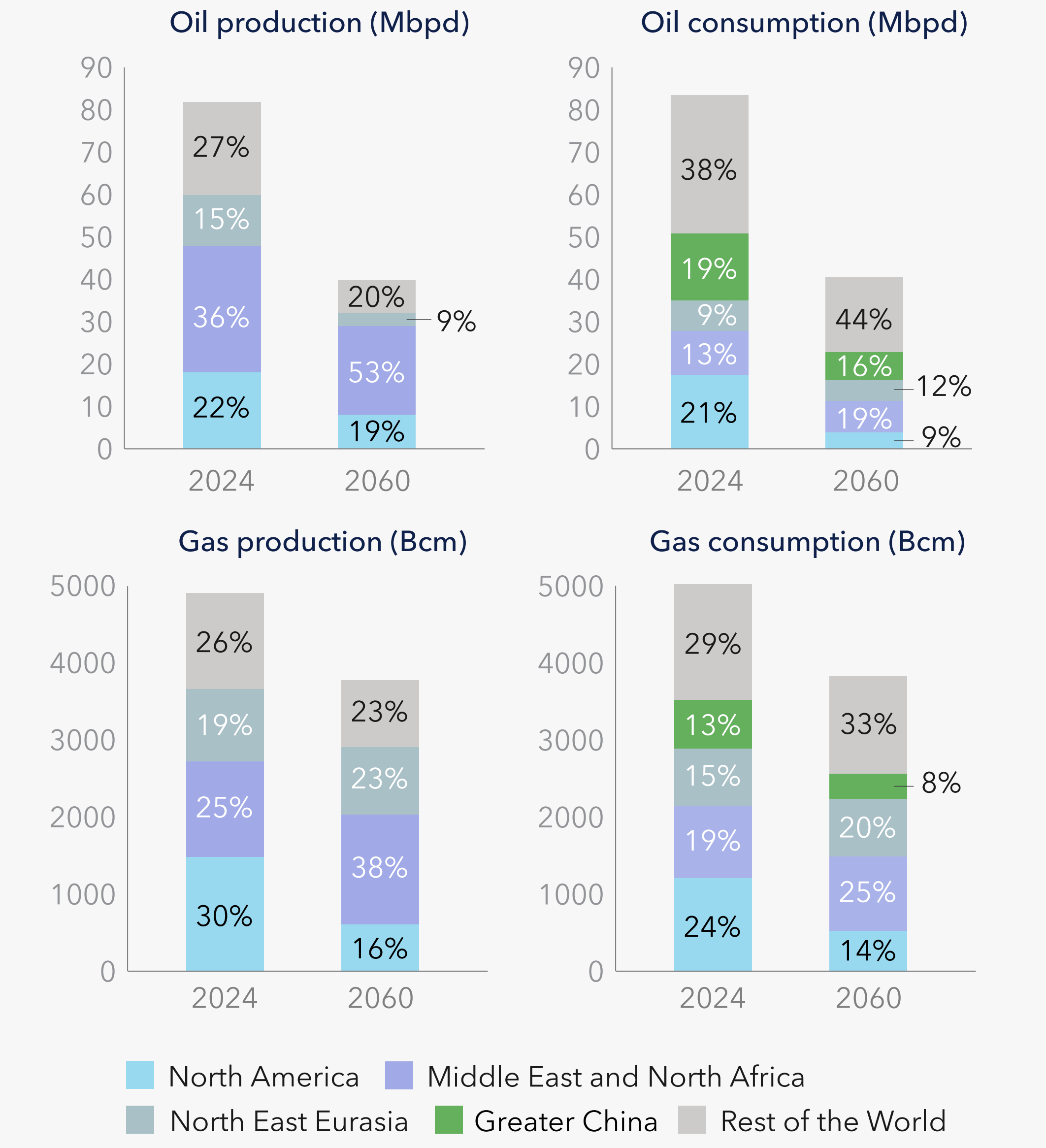


FIGURE 5.1 |



Oil and gas production and consumption overview (2024 vs. 2060)



Regions

Greater China remains the top coal producer and consumer through 2060, followed by the Indian Subcontinent. However, their demand reduces by 87% and 63% respectively.

The Middle East and North Africa (MEA) remains the largest oil producer, despite its output falling, with its global share rising from 36% to 53%. North America's production drops from 18 to 7.5 Mbpd, maintaining a 19% share. By 2060, MEA and Greater China become the largest consumers, 19% and 16% share respectively, overtaking North America.

In 2024, gas production was led by North America (30%) and MEA (25%). By 2060, MEA leads with 38%, followed by North East Eurasia at 23%. North America makes up one quarter of global demand, but it is overtaken by MEA and North East Eurasia by 2060, with those regions taking a 25% and 20% share respectively.

5.1 COAL

Global coal demand grew by 1.5% in 2024 to reach 8.8 Gt. This growth was driven primarily by the power sectors in China, India, and South East Asia that offset declines in North America, Europe, and the OECD Pacific. With China accounting for roughly 60% of global demand, its trajectory heavily influences the overall outlook. In 2025, global demand remains elevated, but we expect it to plateau by 2026 and then decline to around 1.5 Gt by 2060.

Sectoral and Regional Demand

Coal remains central to power generation and manufacturing, accounting for 67% (115 EJ) and 27% (45 EJ) respectively of total coal demand in 2024. These shares shift significantly by 2060 (Figure 5.2). As renewables rapidly replace coal in power generation, the share of coal used in manufacturing surpasses that in power around mid-century. Manufacturing demand declines more slowly than in the power sector due to the difficulty and expense of decarbonizing high-temperature processes. Electricity and hydrogen adoption will be key to displacing coal in industrial use. By 2060, total demand falls to 32 EJ, with only 8 EJ used in power and 19 EJ in industry.

- China, the largest consumer, sees total demand drop from about 100 EJ in 2024 to 13 EJ in 2060, with power use plunging 95%. Manufacturing also declines, but more moderately, owing to the persistence of coal use in hard-to-abate sectors like steel and cement until mid-century.
- India's demand rises to 30 EJ by 2030, driven by growth in both power and manufacturing, then falls to 26 EJ by 2040 and 9 EJ by 2060. Coal use in manufacturing remains relatively resilient, around 6 EJ through to 2060, reflecting slower adoption of clean industrial heat.
- South East Asia's demand declines modestly from 10 EJ in 2024 to 8 EJ by 2040, then drops by half by 2060. Like India, coal use in manufacturing holds relatively steady before tapering after 2040.
- Other regions experience the steepest declines, with combined coal demand falling from 37 EJ in 2024 to 6.6 EJ in 2060, a drop of over 80%, with nearly complete elimination in the power sector.

Production and trade

Global coal production hit an all-time high in 2024, surpassing 9 Gt. This record was driven by increased output in China (+1%), India (+5%), and Indonesia (+8%), which together accounted for over 70% of global supply. Most of this coal was consumed domestically. However, demand in import-dependent regions like India, South East Asia, and China increased in 2024 (IEA, 2024).

Despite the present highs, coal demand is on the brink of a cliff. By 2040, we project total hard coal production to drop to 4,630 Mt, and brown coal to 330 Mt. By 2060, these numbers fall drastically to 1,450 Mt (hard coal) and 80 Mt (brown coal), reflecting aggressive decarbonization policies, rising renewable adoption, and structural demand decline (Figure 5.3).

We expect trade flows – primarily from Indonesia, Australia, Russia, and South Africa to India, China, and South East Asia – to remain directionally stable but shrink in volume, entering a long-term contraction. India's push for self-reliance, China's declining imports, and import phase-outs in Europe and North East Asia will drive this downtrend.

China drops by 44 EJ while India increases by 2 EJ to 2040
Coal regional and sectoral demand (EJ/yr)

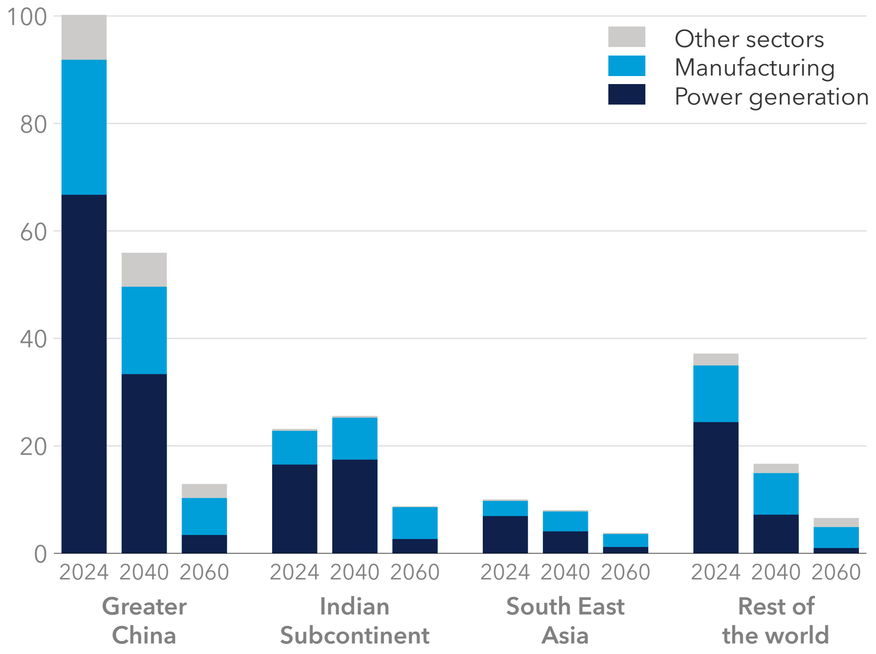


FIGURE 5.2 | Historical data source: IEA WEB (2025)

Brown coal almost disappears in 2040
Coal regional production (Gt/yr)

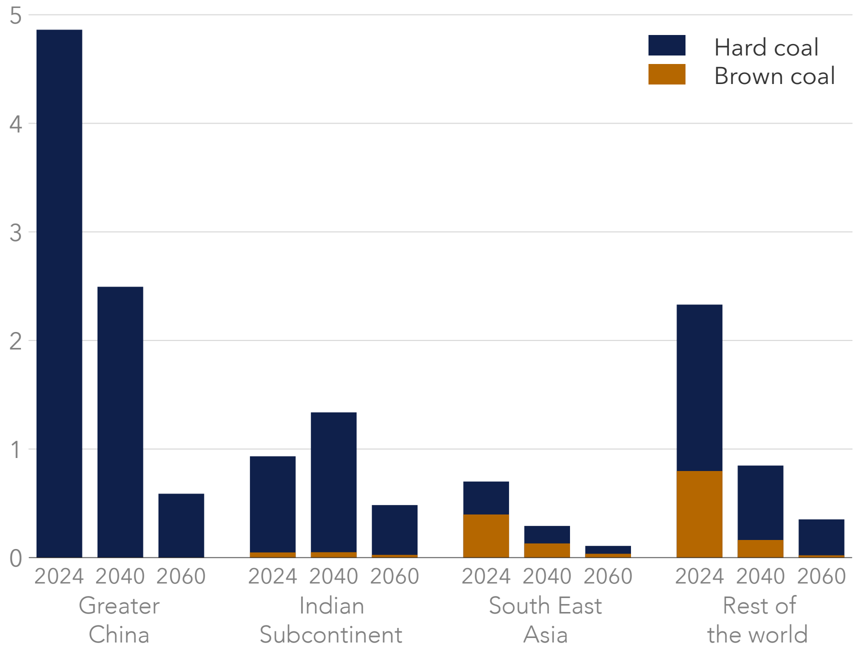


FIGURE 5.3 | Historical data source: IEA WEB (2025)

5.2 OIL

Global crude oil production remained stable from 2023 to 2024 at around 82 Mbpd. A 2% drop in the Middle East due to OPEC+ cuts offset a 4% rise in the US output. In 2025, it increased by 1 to 1.5%, due to strong non-OPEC growth led by the US, Brazil, and Guyana. We forecast a 3 to 4% rise over the next two years (about 86 Mbpd), driven mostly by the Middle East, followed by a plateau and then a visible decline starting after 2032, with production halving by 2060.

From 2015 to 2024, the US accounted for 90% of global oil supply growth, while China drove 60% of demand growth. However, this dynamic is shifting. Oil demand in North America has plateaued and in China is nearing its peak due to rising EV adoption, LNG use in transport, rail expansion, and structural economic changes. At the same time, supply growth in the US is slowing as investment declines, though it remains the leading non-OPEC+ contributor. The Middle East is poised to increase production and reclaim a larger share of global supply. Oil demand continues to grow in India, sub-Saharan Africa, and South East Asia, driven by economic expansion and rising transport needs. By 2060, we expect Greater China, the Middle East and North Africa, and the Indian Subcontinent to become the top three oil-demand regions, reflecting the broader trend of earlier demand peaks in high-income countries and later in lower-income regions (Figure 5.4).

The global oil market continues to navigate significant uncertainty driven primarily by demand-side pressures. Fears of an impending recessionary environment, exacerbated by trade and tariff policies, are weighing heavily on prices. This short-term pressure exists alongside a more profound long-term concern: the likelihood, as signalled by a number of mainstream forecasts, of demand peaking within the next five years and declining within the decade. This will introduce a dynamic that the oil market has not faced since the inception of the 'Oil Age' in the late 19th century.

Figure 5.5 illustrates the transformation of global sectoral oil demand between 2025 and 2060. While total demand increases slightly toward 2030, a deep structural shift has already begun, with transport demand peaking at 116 EJ (a 67% share). By 2040, transport demand declines to 98 EJ, driven by rapid EV adoption, fuel switches in other sectors, and fuel efficiency gains. By 2060, it falls nearly 60% from its peak to 47 EJ. Even then, this still accounts for 60% of oil demand. Demand in other sectors also trends downward, with combined consumption in manufacturing and other sectors falling from 33 EJ in 2025 to 14 EJ by 2060. In contrast, non-energy use sees a modest rise to 26 EJ by 2030, remains flat through 2040, and declines slightly to 22 EJ by 2060. This represents a 27% share and underscores the enduring role of petrochemicals in a transitioning energy system.

Middle East and North Africa increase its share in production by 10% in the next 5 years
Oil production and consumption (Mbpd)

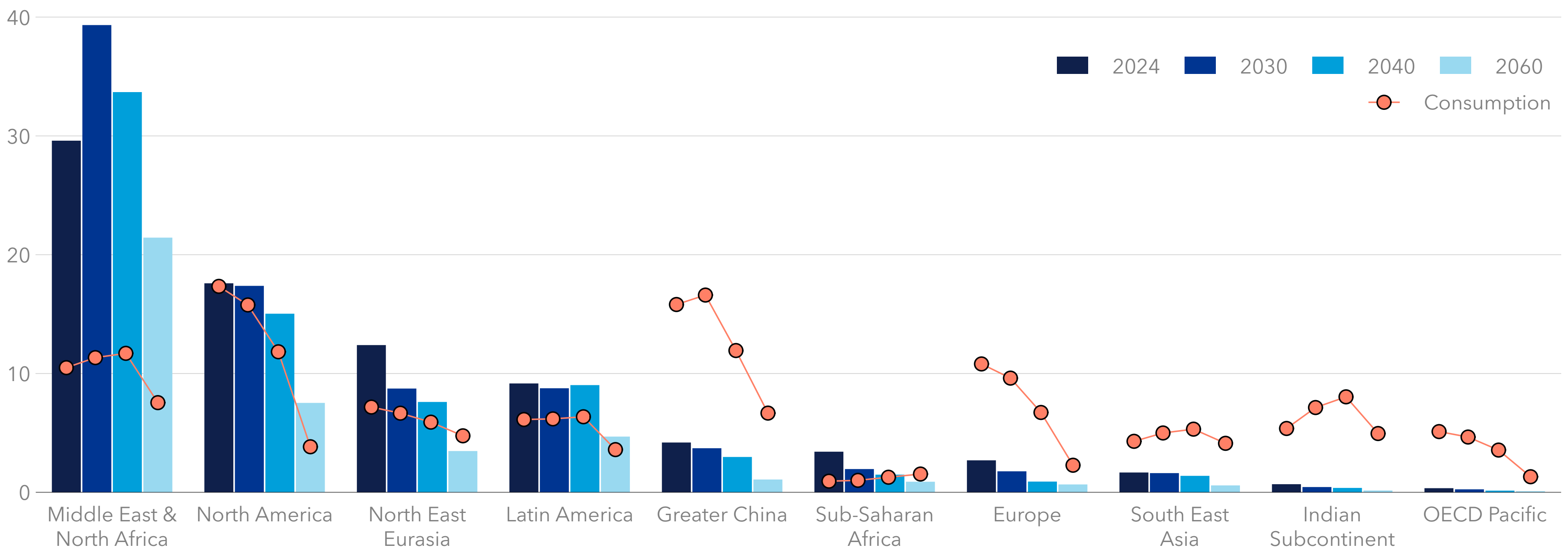


FIGURE 5.4 |

Transport is the biggest contributor to oil decline
World oil demand by sector (EJ/yr)

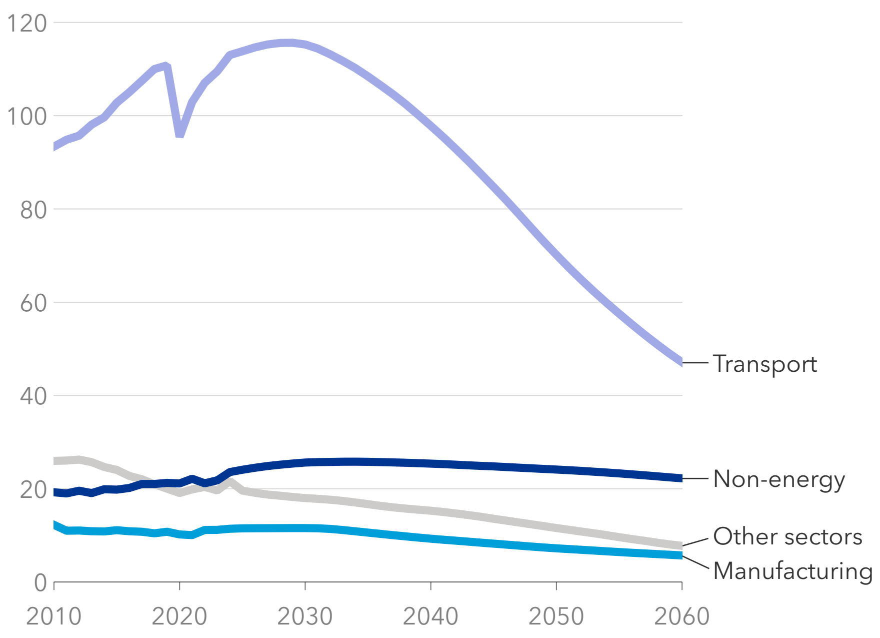


FIGURE 5.5 | Historical data source: IEA WEB (2025)

By 2060, we expect Greater China, the Middle East and North Africa, and the Indian Subcontinent to become the top three oil-demand regions.

Over the past five years, oil has consistently accounted for around 27% of the global primary energy supply. We expect this share to remain steady through 2030 before gradually declining to 17% in 2050 and 13% by 2060. In 2024, global oil demand growth slowed significantly, increasing by just 0.8% (0.8 million barrels per day) to reach 170 EJ. This sluggish growth trend continues into 2025, with demand expected to rise by only 0.7 Mbpd. The slowdown reflects the end of the post-pandemic travelling rebound, weakening industrial activity, and the growing adoption of EVs.

Demand

The expansion of the transport sector, due to population and economic growth, has been the main growth driver for oil demand. EV sales are gaining momentum and will dominate new passenger and commercial vehicle sales around 2033 and 2040, respectively. This places a dampener on oil. Oil road transport demand is likely to plateau at 88 EJ/yr within the next five years before declining from 2030 onwards, falling to 31 EJ/yr by 2060 (Figure 5.6). Between 2025 and 2030, the global EV fleet quadruples from 56 million to 211 million, replacing about 2.7 Mbpd of oil use.

Oil use in aviation, shipping, and rail transport (collectively termed 'other transport' in Figure 5.6) will initially grow for a few years. Thereafter, the shift toward biofuel, green ammonia, e-kerosene and other low-carbon fuels will reduce this aspect of oil demand by 41% from 27 EJ/yr in 2024 to 16 EJ/yr in 2060. See Section 2.6 for additional details on transport fuels.

Oil's second largest sectoral demand is as feedstock for non-energy use, mostly plastics production and non-petrochemical industries. The share of non-energy in oil demand, which does not entail any direct CO_2 emissions, has been around 14% for the last decade. With declining oil use for most energy purposes, the share of non-energy use in oil demand rises from 14% today to 27% in 2060. In absolute terms, oil demand for non-energy use will increase from around 24 EJ/yr today to 26 EJ/yr by 2030, then slowly decline to 22 EJ/yr by 2060, due mainly to lower virgin plastics production caused by demand-side reduction, substitution measures, and higher rates of recycling (see Section 5.4 for more details).

Manufacturing is the third largest oil user. Demand will decline slightly from the current 11 EJ/yr to 6 EJ/yr, retaining a 6% share of oil demand by 2060.

Oil and its derivative products are also used in buildings, power, 'other' sectors, and for producing the oil itself. Nevertheless, these uses are small (12% of total oil demand) and will remain so throughout our forecast period.

Peak oil demand and production vary significantly by region (Figure 5.4). High-income regions peak early while low-income regions peak later or outside our forecast period. Much like the broader energy demand trend, global oil demand is shifting eastward and southward. North America led global oil demand for decades, but rising electrification in transport means Greater China will overtake it after 2026. Beyond 2040, the Middle East and North Africa will surpass China to become the world's largest oil-consuming region. Although North America's absolute oil demand will decrease due to EV growth, we project its demand per capita will remain the highest in the world for the next two decades. By 2060, North East Eurasia will have the highest oil demand per capita followed by the Middle East and North Africa and North America (Figure 5.7). Sub-Saharan Africa will maintain a much lower oil demand per capita than the other regions throughout the forecast period.

EV growth is the main reason for oil decline

Oil demand by sector (EJ/yr)

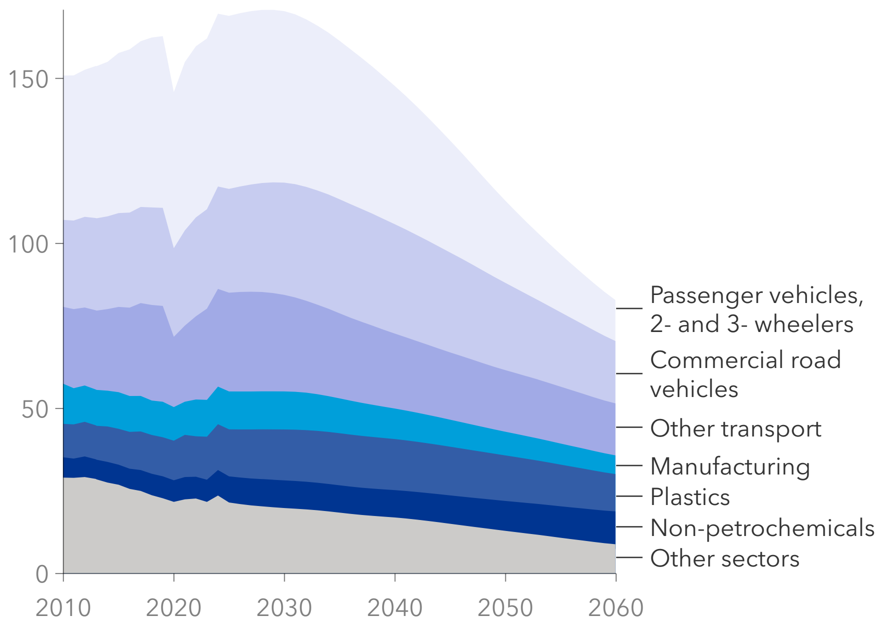


FIGURE 5.6 | Historical data source: IEA WEB (2025)

North America stays the biggest consumer per capita for the next two decades

Crude oil demand per capita by region (bbl/person-yr)

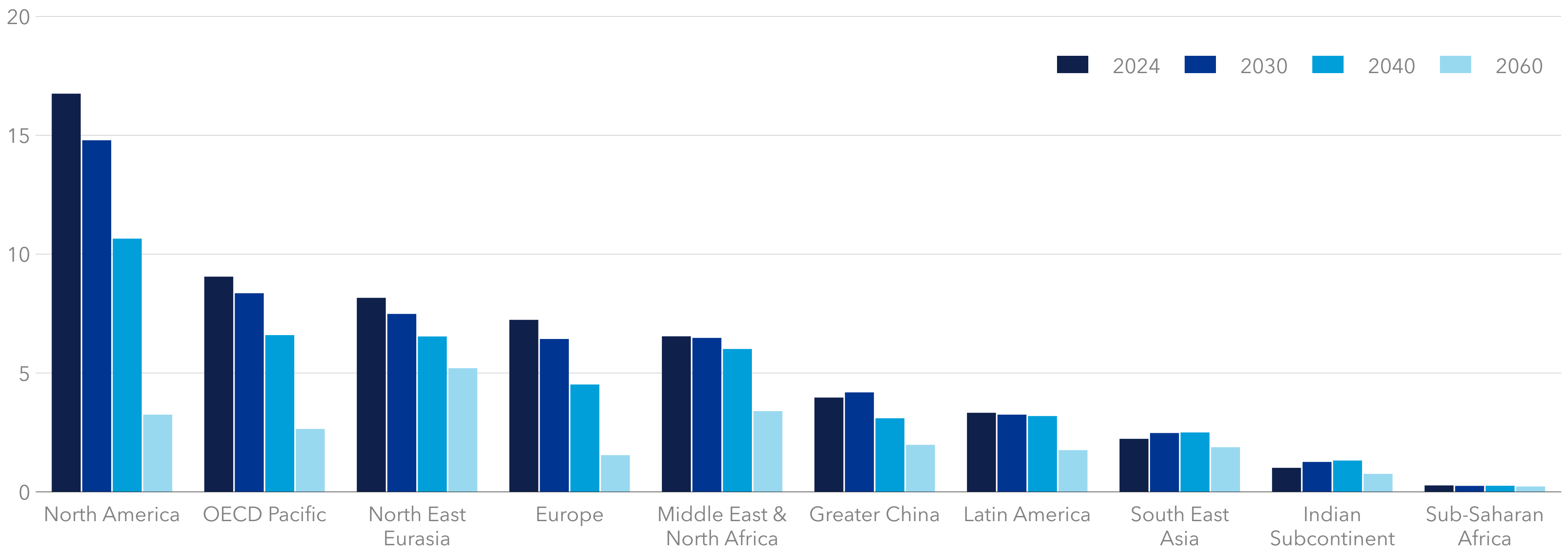


FIGURE 5.7 |

Production and trade

The Middle East and North Africa, North East Eurasia, North America, and Latin America are net oil exporters and will continue exporting throughout our forecast period (Figure 5.8). Greater China, Europe, the Indian Subcontinent, OECD Pacific, and South East Asia will remain net oil importers, with import volumes projected to decline sharply for Greater China, Europe, and OECD Pacific, while the Indian Subcontinent and South East Asia see substantial increases in their oil imports. Latin America will be a net oil importer before the end of this decade.

Lower oil prices and demand expectations are set to result in a 6% fall in upstream oil investment in 2025, the first year-on-year decline since the Covid slump in 2020 and the largest since 2016. While spending in natural gas fields is set to maintain the levels seen in 2024, lower expenditure on oil brings expected upstream oil and gas investment for 2025 to just under USD 570bn, a decline of around 4%. Global refinery investment in 2025 is set to fall to its lowest level in the past 10 years (IEA, 2025).

We forecast that while all regions will reduce crude production, the Middle East and North Africa's share – which has been about 35% for the last three decades – will increase to 53% in 2060 due to rapid reductions in other regions (Figure 5.4). Production in the Middle East and North Africa will climb from 30 Mbpd in 2024 to 40 in 2030 Mbpd then decline to 21 in 2060. The region has the lowest cost-per-barrel oil production, a critical factor for market share retention as demand reduces and market competition tightens. In a declining market, prices are more likely to reflect marginal production costs. This favours the region's cost advantage. Nevertheless, importer regions will continue to focus on energy security, accelerating renewables deployment at regional and local levels. Consequently, oil's significance in the geopolitical landscape is likely to slowly wane in the coming decades.

We stress that uncertainty over where oil will come from is high. In our ETO model, oil production equals demand and high-cost regions will not develop their oil resources if cheaper oil can be supplied elsewhere. Although limited storage means that global oil production will always equal demand over time, regional distribution – skewed by non-market factors like subsidies and trade barriers – might not follow the same disciplined pattern assumed in our model. However, declining oil demand will invariably make it less attractive for the industry to expand production into challenging environments such as deep water, high pressure, and remote locations like the Arctic. OPEC will face strategic choices as demand plateaus and declines also. It may defend market share by maintaining high output at the cost of lower prices, or it could manage supply to support prices through coordinated cuts.

Middle East and North Africa increases export share

Oil export by region (Mbpd)

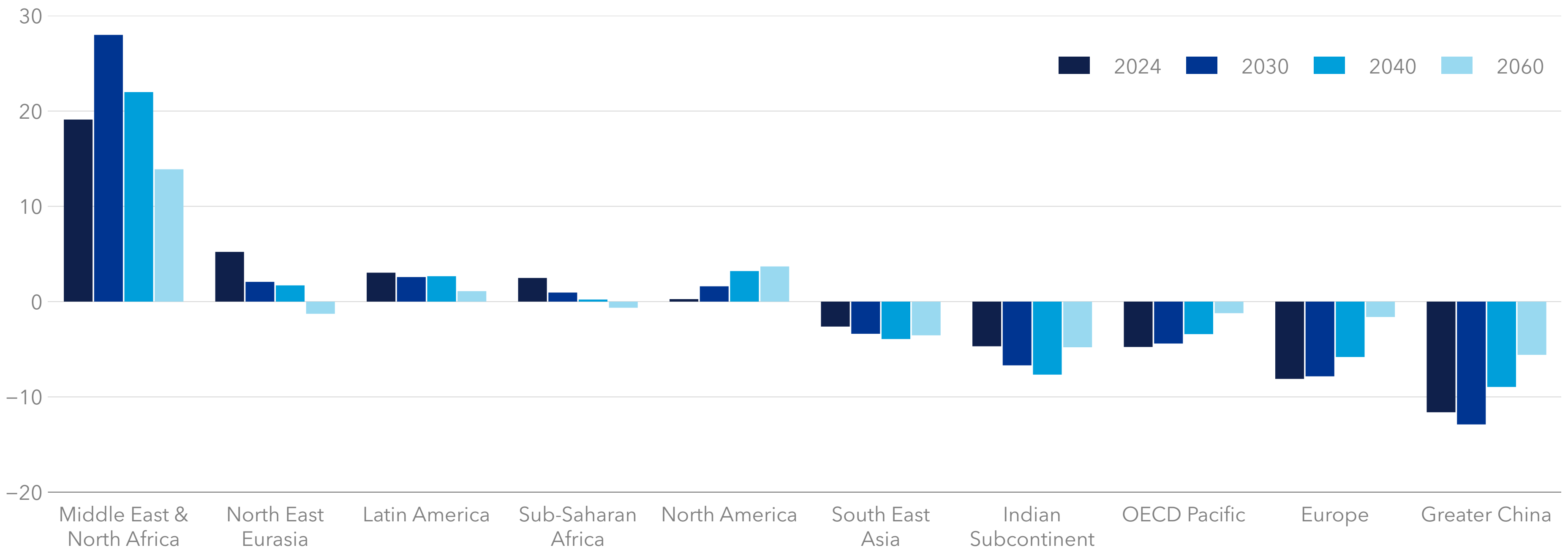


FIGURE 5.8 |

5.3 NATURAL GAS

Between 2023 and 2024, demand for natural gas (including LNG) rose by 2.5% to 174 EJ, with 85% of this increase driven by the power sector. We expect that trend to ease with power sector gas demand rising only slightly for the next two years before plateauing and then declining from 2035 due to the expansion of renewable generation.

Between 2024 and 2040, natural gas demand will increase across all sectors (Figure 5.9). From 2040 to 2060, gas demand declines across all sectors, reflecting fuel switching (electricity and hydrogen) and improved energy efficiency – except for hydrogen production, which continues to grow.

Figure 5.10 shows natural gas production and consumption across the 10 world regions we model. The picture is one of stalling and then falling demand patters in Europe, North America, Latin America, and OECD Pacific. The Middle East, North East Eurasia, and China will register modest growth to 2040 before sharp declines set in. It is only Sub-Saharan Africa and the India Subcontinent where we expect to see continuous growth to 2060s, but both markets remain relatively small. In aggregate, global gas demand will increase by about 5% within the next 10 years to around 5,500 Bcm and plateau there until 2040 before declining to 3,800 Bcm in 2060, 25% lower than the demand today.

As fossil fuel demand declines and shifts regionally, infrastructure adaptation becomes essential. North America in particular will face the repurposing or retirement of infrastructure across the supply chain. In contrast, supply hubs such as the Middle East and North East Eurasia will require export upgrades, especially for gas. Some gas infrastructure – like pipelines, storage, and port facilities – can be partially repurposed for low-carbon alternatives, particularly hydrogen. This includes blending hydrogen into gas networks or converting storage sites. Investment will prioritize flexible systems that support declining fossil flows while enabling future use in emerging clean energy markets.

From 2040 to 2060, gas demand declines across all sectors, reflecting fuel switching and improved energy efficiency.

Gas demand starts declining only after 2040

Natural gas demand change in different sectors (EJ/yr)

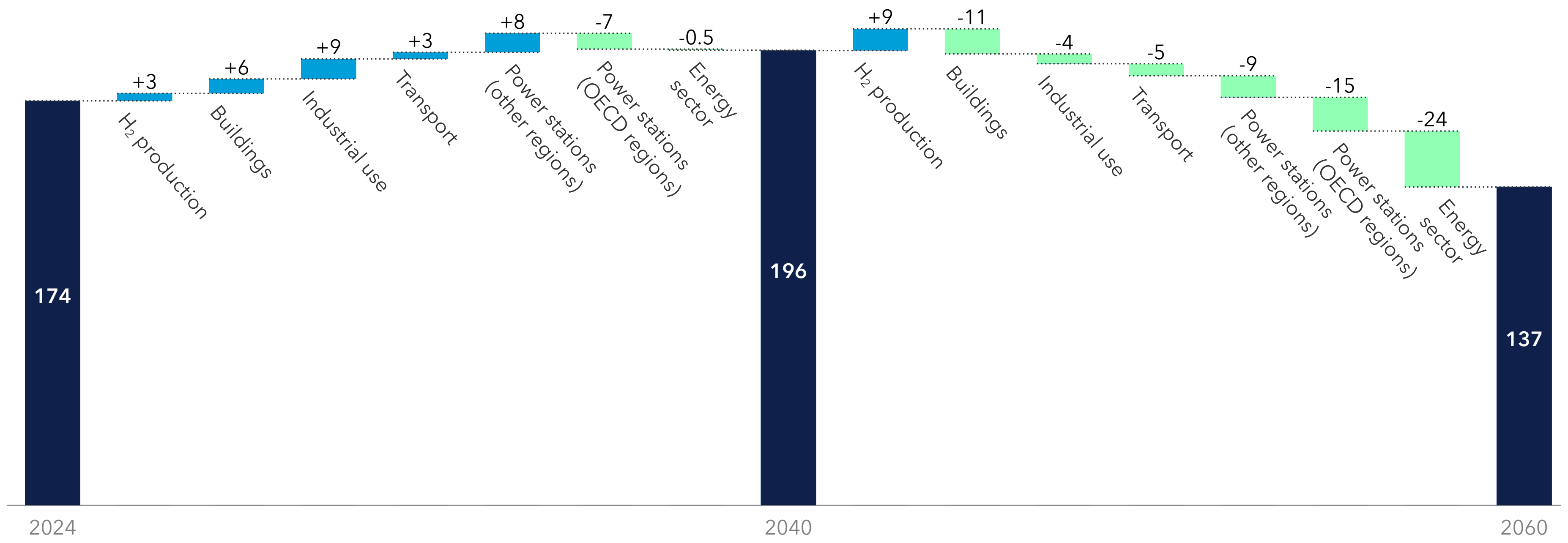


FIGURE 5.9 | Industrial use combines manufacturing and non-energy demand. OECD regions: North America, Europe, and OECD Pacific.

Middle East and North Africa overtakes North America in natural gas production

Natural gas production and consumption (Bcm/yr)

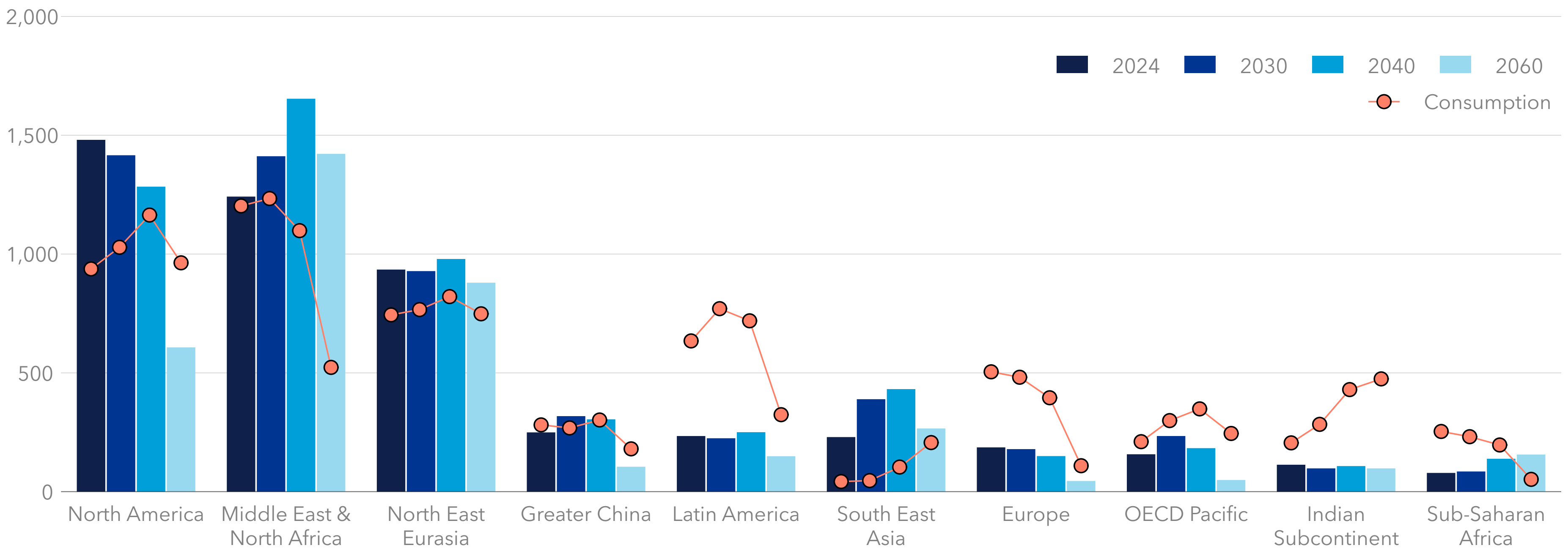


FIGURE 5.10 |

Over the last decade, natural gas has consistently accounted for around 27% of the global primary energy supply. We forecast that it will maintain this share until 2040 before declining to 24% in 2050 and 20% in 2060. Future natural gas demand will vary by region, typically increasing in low- and middle-income regions and reducing in OECD regions (Figure 5.10). There will also be demand for natural gas in new sectors, particularly with increasing use in maritime transport and as a feedstock for making blue hydrogen and ammonia.

Demand

Natural gas demand has grown over the past two decades, but the distribution between sectors has remained relatively consistent (Figure 5.11). Total natural gas demand in 2024 was 170 EJ. This will increase to 191 EJ in 2038 before declining to 164 EJ in 2050 and 131 EJ in 2060.

- Over the past two decades, power generation has dominated natural gas demand, accounting for approximately 35% of total use. We expect power to maintain this share until 2035 before reducing to 7% (20 EJ) by the end of our forecast period due the expansion of renewable energy sources with much of that coupled with battery storage.
- Demand for gas from the buildings sector will increase from 38 EJ in 2025 to 44 EJ in 2040 as it replaces coal and biomass in cooking and heating. However, it will reduce to 33 EJ by 2060 due to increased efficiency in buildings and electrification (e.g. heat pumps).
- We project demand for gas in manufacturing to stay almost constant at the present level of 30 EJ throughout the forecast period as it replaces coal in some processes and is replaced by electricity and hydrogen in others.
- Starting from a relatively low baseline of 7 EJ, gas demand in the transport sector will rise to 10 EJ by 2030 and stay at that level for a decade before declining to 5 EJ by 2060 as momentum builds in the replacement of gas by hydrogen derivatives such as ammonia and e-fuels in shipping.
- The share of non-energy applications (largely petrochemicals) in gas demand will increase from current 10% to 15%. It also increases in absolute value from 17 EJ to 20 EJ.
- We expect own use (demand from the oil and gas and energy industries during production and distribution) currently at 21 EJ, to remain steady in the mid 2030s before halving to 11 EJ by 2060. Efficiency gains, production facility electrification, and reduced flaring will contribute to decreases in own use. Some of this use in the energy sector will be for the liquefaction and regasification of gas transported as LNG.
- Additionally, we project gas demand for hydrogen and ammonia production for energy related purposes will increase from negligible levels in 2025 to 13 EJ by 2060.

Gas demand for power generation shrinks 62% to 2060

Natural gas demand by sector (EJ/yr)

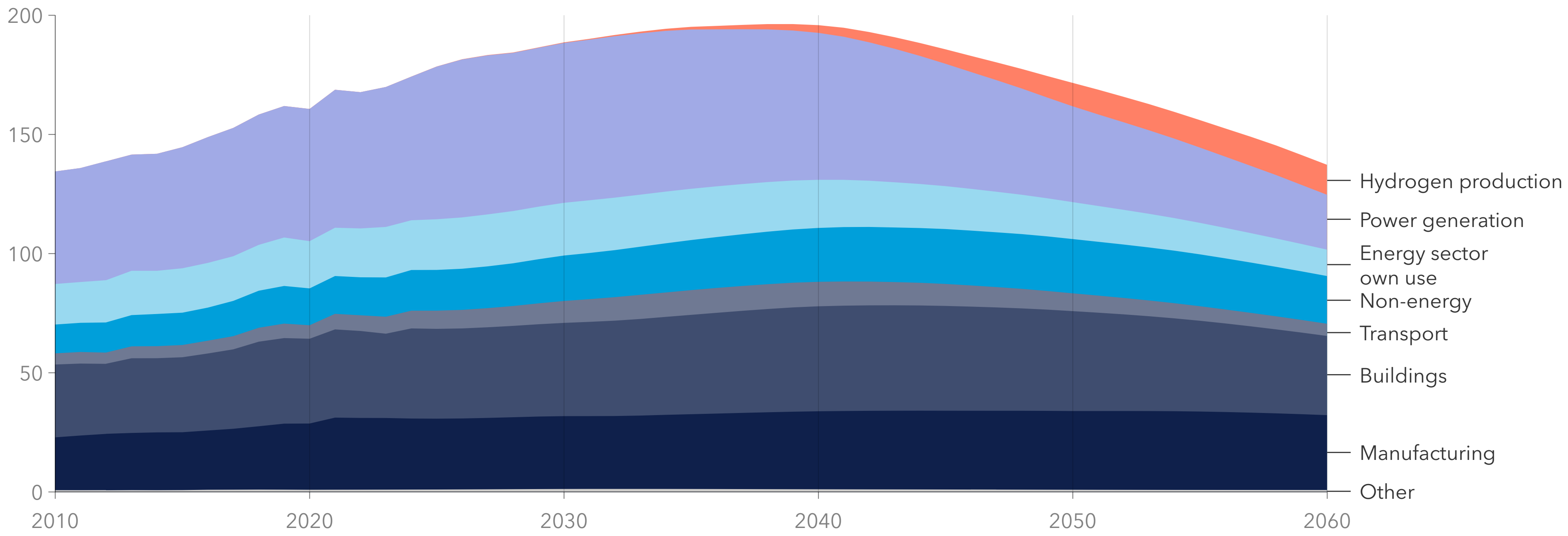


FIGURE 5.11 | Historical data source: IEA WEB (2025)

Production and trade

Global natural gas production will mirror demand patterns – i.e. grow for the next decade, stabilize until 2040, then gradually decline to 75% of its current level by the end of our forecast period. Although a growing share of natural gas will be exported as LNG, gas remains a much more regional commodity than oil. As a result, gas production tends to follow regional demand more closely than oil. This helps explain, for example, the significant decline in gas production in North America.

By 2060, Middle East and North Africa gas production will have increased by 17%, expanding its share of production from 15 to 40% (Figure 5.10). In a shrinking market, gains in the Middle East and North Africa will come at the expense of production and market share reductions in North America and North East Eurasia (Figure 5.12).

- The Middle East and North Africa, North America, and North East Eurasia were the top natural gas exporting regions in 2024. The Middle East and North Africa remains the biggest exporter during our forecast period, reaching 460 Bcm in 2040. We expect North East Eurasia's export volume to be stable. Conversely, we project North America's export volume to gradually decrease by 10% in 2040 and 60% by 2060.
- OECD Pacific has considerable interregional trade, with Australia as the world's third-largest LNG exporter and Japan and South Korea as major importers. However, increased production in Australia combined with decreased demand in Japan and South Korea (as the shares of nuclear and renewables increase in power) will lead to a supply surplus, shifting the region from a net importer to a net exporter.
- Europe's import trend will likely continue through 2030, then steadily decline to 28% of its current level by 2060 as gas demand decreases sharply. Alongside decarbonization, energy security concerns are also driving the reduction in imports.
- Greater China and the Indian Subcontinent both face high demand with limited domestic natural gas resources. In Greater China, gas imports will rise until 2030 and then decline through 2060 as domestic consumption decreases. We expect the Indian Subcontinent to significantly increase its LNG imports to meet a nearly three-fold surge in demand.

The cost of delivering gas from producer regions to consumer regions influences trade. Gas transport is expensive and accounts for a significant proportion of the cost of delivered energy. Both pipeline and LNG transport will increase even when global gas demand decreases because of a shift in demand patterns and diversification. Even though piping is cheaper than shipping gas for shorter distances, we still expect LNG to further increase its share due to its greater efficiency for long-distance transport and the growing desire of importing countries to increase energy security and diversify their supply sources.

We project global LNG liquefaction capacity will reach 940 Bcm by the end of 2028 with major contributions from the US (doubling from 122 Bcm to 244 Bcm) and Qatar (from 106 Bcm to 150 Bcm) (Incorrys, 2024). On the import side, Europe's regasification capacity is set to rise from 322 Bcm to around 365 Bcm by 2028 (IEEFA, 2025), while China, India, and Vietnam plan substantial increases by 2030 (from 78 Bcm, 36 Bcm, and 24 Bcm to 128 Bcm, 78 Bcm, and 58 Bcm, respectively) (Offshore technology, 2025). Despite the LNG boom, geopolitical risks are renewing interest in alternative pipeline routes like Russia's proposed Power of Siberia 2 to China.

By 2060, Middle East and North Africa gas production will have increased by 17%, expanding its share of production from 15% to 40%.

Middle East and North Africa remains the biggest exporter during our forecast period

Natural gas export by region (Bcm/yr)

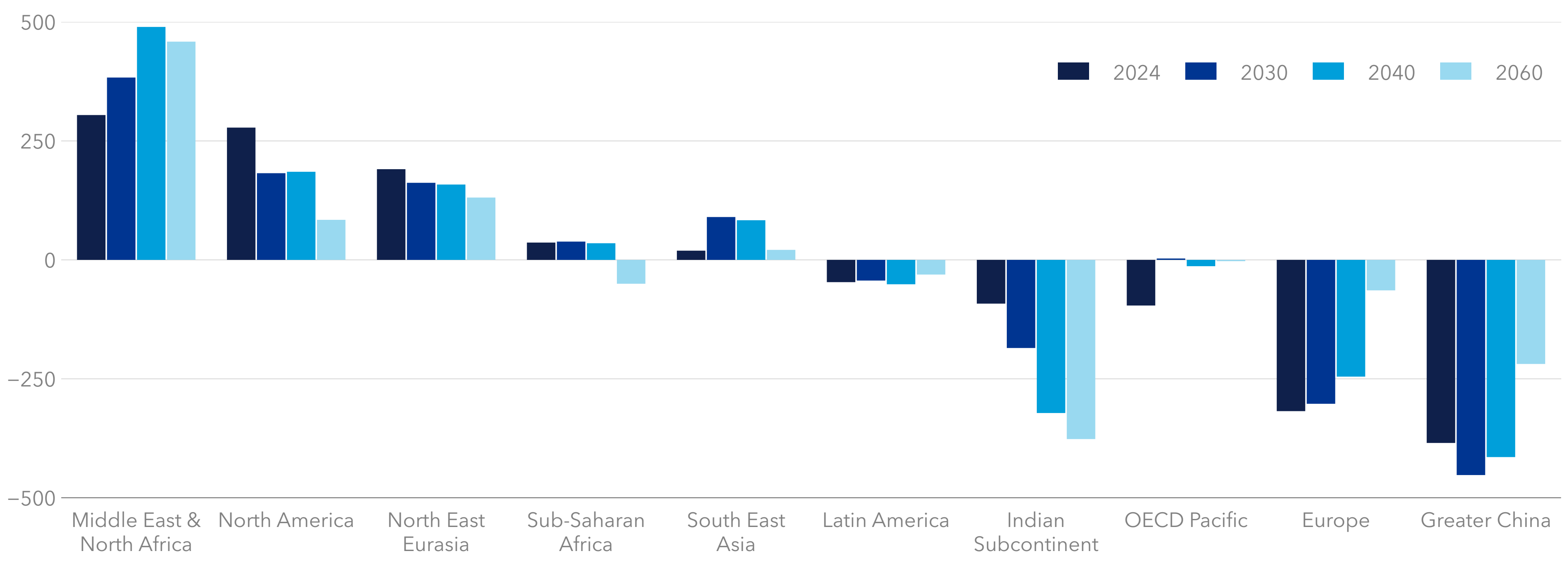


FIGURE 5.12 |

5.4 NON-ENERGY DEMAND

While the petrochemical sector is widely expected to be oil's last major growth frontier, a combination of recycling, efficiency, and substitution will cap and then reverse this growth within 15 years.

Our forecast for a mid-2030s peak in virgin feedstock demand is the result of a fierce tug-of-war. A growing global population and economy will naturally push for more fossil-based material such as plastics, asphalt, or fertilizers. Unlike in most other sectors, no alternative to oil and gas exists at scale to produce these materials.

However, this growth will be halted by powerful counterforces creating a definitive ceiling and leading to non-energy demand peaking in the 2030s (Figure 5.13).

Fast-growing circularity, the primary driver of the peak

Plastics production is the main demand sector for non-energy purposes. We project that demand for plastics will nearly double by 2050 despite efforts for systemic efficiency (doing more with less) and targeted substitution (e.g. single-use plastics bans).

However, the need for virgin fossil fuel feedstock will rise by only a third and peak in the early 2040s. The difference will be met by a massive expansion in recycling. Well-established mechanical recycling will expand and grow in all regions (Figure 5.14). It will surge from meeting 7% of demand today to 32% by 2060. The technology readiness of chemical recycling as a new feedstock source will steadily progress over our forecast period, supplying over 2 EJ per year of recycled fuel directly back into steam crackers, corresponding to 6% of the demand for plastics in 2060.

Feedstock choice is regional

Today's fuel mix for non-energy use is dominated by oil and natural gas which met 54% and 42% of demand in 2022, respectively. Coal covers the rest of the mix, with China using 90%, mainly for ammonia and methanol production.

Non-energy demand will peak in the 2030s
World non-energy demand by sector (EJ/yr)

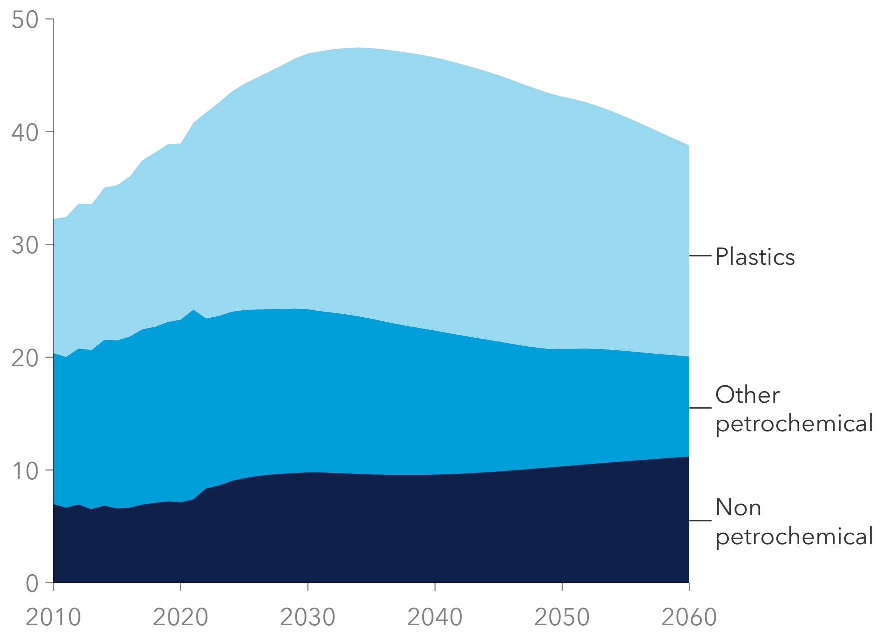


FIGURE 5.13 | Historical data source: IEA WEB (2025), DNV analysis

Feedstock choice is dependent on local availability and prices and historically installed capacity. For instance, plastics production requires primary chemicals like ethylene or propylene, which can be obtained from cracking oil or from natural gas. North America relies on natural gas as a feedstock due to the abundance of ethane, a by-product of natural gas extraction. Regions with little fossil-fuel extraction, such as Europe or Greater China, will usually use naphtha, a fraction of oil which can be easily imported.

80% of ammonia is produced from natural gas by steam-methane reforming. We expect this share to stay constant, with an increasing uptake of carbon capture. Coal gasification will be progressively phased out and will represent 7% of ammonia production in 2050 versus 18% in 2022. Ammonia produced via electrolysis-based hydrogen will cover almost a fifth of demand, but subsequent reuse of CO_2 in the process to produce urea will limit the uptake of this alternative.

Plastics feedstock increasingly relies on recycled material
Global plastics demand (Mt/yr)

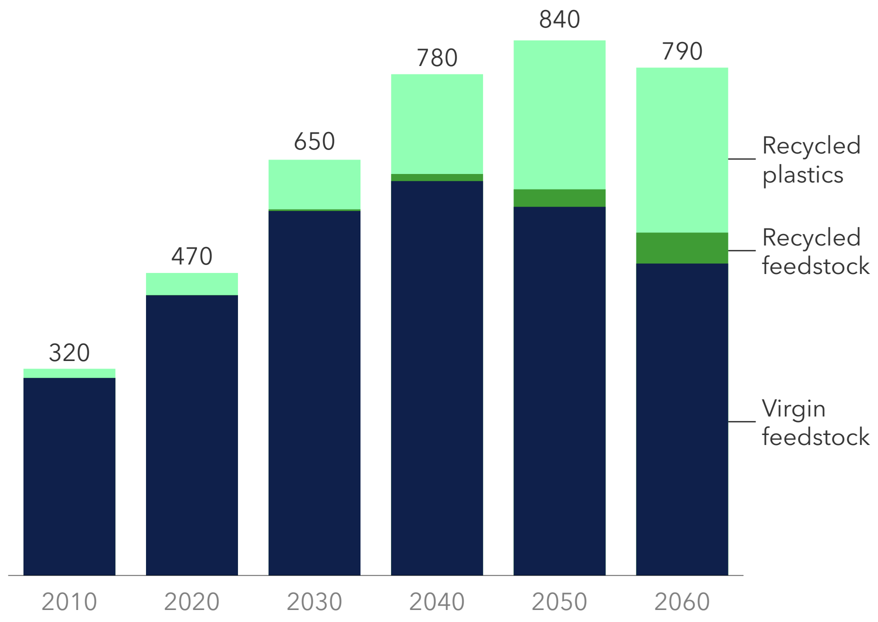


FIGURE 5.14 | Recycled feedstock replaces virgin oil and gas in traditional production routes.

Turbulence on the horizon?

Oil and gas producers will increasingly target and compete for market share in petrochemicals. As demand declines in other sectors like road transport, non-energy presents opportunities for growth. This is especially critical for oil, with non-energy representing a quarter of demand in 2060, a doubling from today's level.

However, our forecast shows that the industry narrative of petrochemicals as a safe haven for oil and gas demand does not hold. Rather than being a long-term growth engine, petrochemicals are likely to become a time-limited opportunity with market share for virgin feedstock demand becoming fiercely competitive after the mid-2030s peak.

With a forecast declining demand, the risk for global overcapacity and stranded assets is real. This will put an additional constraint on current production infrastructure and drive the integration of refineries and petrochemical plants. Attention will shift from capturing new demand to stealing market share, and refineries banking on petrochemicals for survival will likely face intense margin pressure.

6 POLICY

6.0 HIGHLIGHTS

Uncertainty and complexity are watchwords in the global policy landscape. Security, energy, climate, and industrial policies are becoming entangled in efforts to boost economic competitiveness, while diverging political ideologies usher in a more fragmented world.

Energy security and economic resilience are top priorities for policymakers, directly shaping decisions about critical materials, technology, and supply chain strategies – choices that, in many cases, result in more expensive and complex energy projects.

In our *Energy Transition Outlook*, we model technology selection based on various factors such as cost, revenue, availability, and utility (see Chapter 10). Policy is another factor that impacts decisions and therefore technology uptake. In today's policy and market environment, it is crucial that our forecast reflects that.

Energy projects and transition options are increasingly influenced by inflationary trade tariffs, local content rules, and localization requirements. These add non-cost criterion and premiums. In this Outlook, we account for these policy-driven dynamics by adjusting several key assumptions: GDP projections, manufacturing locations, regionally differentiated technology costs, and the energy sources that different regions are likely to prioritize (see Chapter 1).

In 2024, **143** countries had **renewable power targets**

35 had **renewable targets** for **direct heat**

20 had **biofuel targets** for **transport**

Key policy highlights

- **Climate, energy, and industrial policies are now firmly interwoven with efforts to boost economic competitiveness**. Today, governments increasingly see decarbonization as a means to preserve domestic economic value creation, security, and competitiveness.

- **Policy frameworks will increasingly handle multi-speed transitions across different sectors.** Currently, sector-based renewable targets/policies are less common outside the power sector. As of 2024, 143 countries had renewable power targets, whereas only 35 had renewable targets for direct heat and 20 had biofuel targets for transport (REN21, 2025).

- **Renewable electricity policies are central to wider electrification.** For initial uptake, governments primarily leverage market-based mechanisms like auctions and support technologies such as EVs and battery storage, underpinned by technology fundamentals like low cost and speed to market. For maturing electricity systems with high renewables penetration, the main policy and regulatory aspects relate to market arrangements such as anchoring revenue for available capacity, flexibility and system services, time-of-use tariffs, and modernizing grids (see Chapter 3). These measures also help manage new demand loads like data centres, electrolysers, and EV charging infrastructure; perhaps more importantly, they underpin electrification outcomes in demand sectors.

- **High-income regions and China are focussing policy on hard-to-decarbonize, trade-exposed sectors.** These sectors face global competition, have limited commercially viable decarbonization options, and require complex infrastructure like clean fuels, hydrogen, and carbon capture and storage (CCS). High costs from prospective producers lead to low demand from prospective users with insufficient policy support to bridge the two. The main policy and regulatory aspects include narrowing the cost gap with fossil fuels, supporting early-stage supply, and strengthening demand through direct support and purchase/use obligations to reinforce market offtake. Decarbonization involves multi-decadal investments that require near-term policy certainty on regulation, incentives, and carbon pricing.

- **Climate goals are slipping out of reach** and time is running out to halve CO_2 emissions from 2019 levels by 2030 (IPCC, 2023) even though countries face growing legal risks for inaction considering the recent opinion by the International Court of Justice (2025). Global energy system transformation requires maximum collaboration on technology and knowledge transfer. Yet, international cooperation is at a particularly low point. There is a staggering need for policy leadership that stays focused on the upside of decarbonization and addresses well-known barriers, including immense fossil-fuel subsidies (regularly assessed by the OECD and the IEA), uneven carbon pricing (Section 6.3), and public acceptance (see sidebar).

Social impacts of the transition

The energy transition impacts communities in various ways, affecting local job creation and displacement, household energy costs, economic opportunities, and social equity. In renewable energy projects, especially in high-income areas, we note a trend towards increased use of engagement strategies and greater participation. Specifically, developers are paying more careful attention to the context-dependent needs and potential benefits for local communities. We reflect the varying levels of engagement across regions in our analysis by incorporating a construction time delay factor for renewable energy technologies and nuclear, tailored to each region and technology (see Page 136 of ETO 2024 for further details).

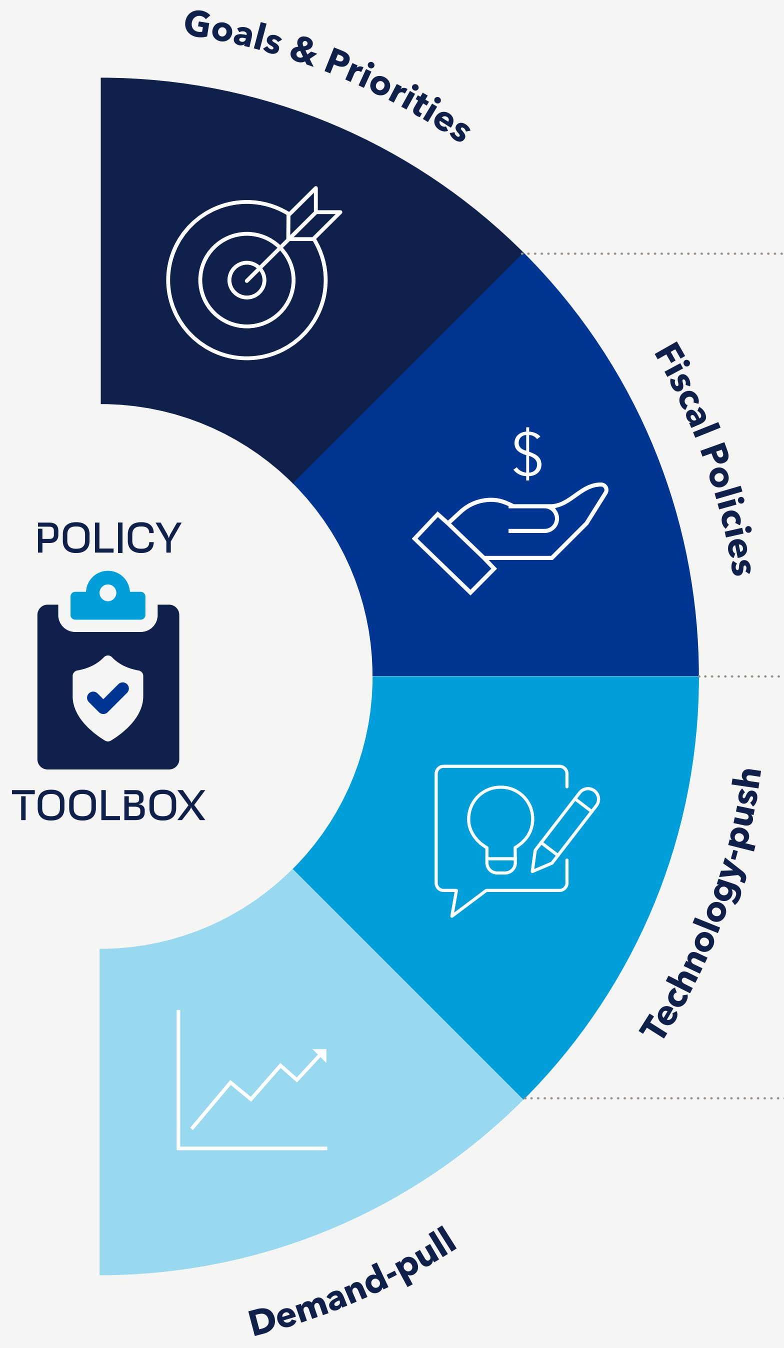
Although Europe has the most advanced and comprehensive social engagement practice, most EU member states' national climate and energy plans (NCEPs) failed to adequately address EU just transition requirements. The introduction of ETS 2 – which put a price on emissions from transport and heating fuels – will impact household finances, yet recent analysis of NCEPs suggests a lack of energy poverty assessments linked to ETS 2 implementation (CAN Europe, 2025). Both policy and private sector decision makers must prioritize recognition and assessment of societal impacts at the project level to achieve fair distribution of burdens and benefits and to help overcome delays in the energy transition.

6.1 THE ENERGY TRANSITION'S POLICY TOOLBOX

Policies influencing energy system evolution include planning, fiscal instruments, technology-push, and demand-pull measures. While it is paramount to put a value and price on carbon to incentivize emissions reduction, current carbon pricing schemes are, in most regions, too volatile and low to drive energy substitution toward less emission-intensive sources.

A policy mix of complementary measures is essential in the early stages of industry development to move projects to implementation in areas such as clean fuels, CCS, and hydrogen, with measures that bridge supply- and demand-side developments to ensure the bankability of large-scale projects and incentivize markets downstream.

Policy toolbox measures are assessed in nine policy areas. We continuously map and assess global, regional, and national proposals and law-making for their likely transition impacts. The nine policy factors implemented in the ETO Model reflect measures such as CAPEX and OPEX support, standards, and taxes. Refer to Chapter 10 (Sections 1 and 4) for further details on policy incorporation into the analysis.



Purpose: Structure and inform national and sectoral policy
- **Plans** informing short- and mid-term priorities, policies, and investment pipelines (e.g. Long-Term Low Emission Development Strategies (LT-LEDS), National Energy and Climate Plans (NECPs) in the EU)
- **Industry or sector agreements** for decarbonization (e.g. IMO, ICAO targets and strategies)
- **Public-private partnerships** for joint innovation undertakings leveraging private sector resources (e.g. the Climate Club for industrial decarbonization, the Carbon Management Challenge on CCS, or the Green Shipping Corridor)

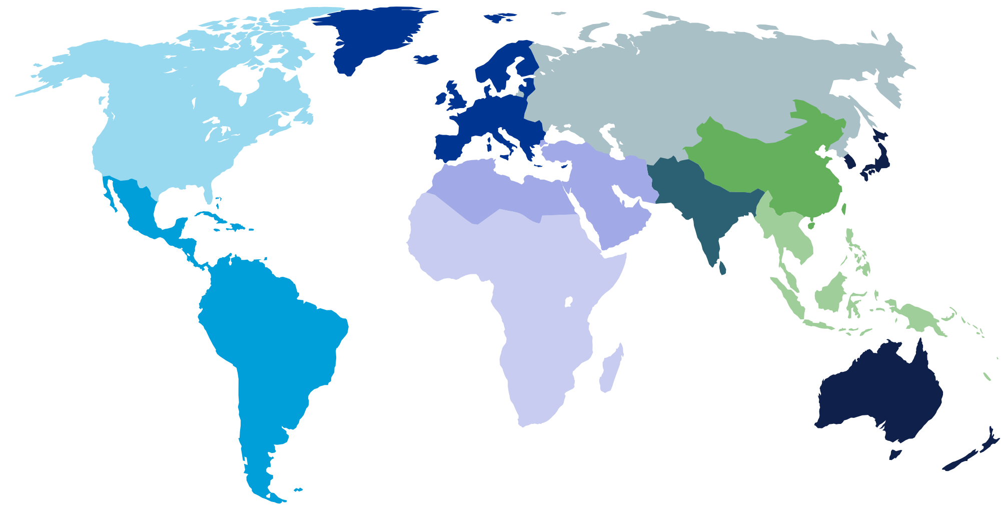
Purpose: Integrate goals and level the playing field
- **Public budgets and spending** to align financial flows with climate goals and low-carbon development
- **Economic instruments** that incentivize emissions reduction and consumer choices in favour of clean energy (e.g. tax credit incentives, carbon tax, emissions trading systems, carbon border adjustment tariffs, energy tax differentiation on effluents and carbon content, fossil fuel subsidy removal)

Purpose: Stimulate technology development and cost reduction
- **Funding** for feasibility studies, RD&D, and capital expenditure (CAPEX) contribution through grants, loans, and investment tax credits to projects and critical supply chains
- **Infrastructure investments** for grids, charging, refuelling corridors, carbon management value chains
- **Technical requirements** for emission limits, emission intensity reductions, fuel economy/efficiency standards
- **Taxonomy** classifying climate-compatible economic activities and compliant sustainability investments

Purpose: Stimulate demand and incentivize market uptake
- **Mandates** for emission reduction and energy substitution (e.g. targets for low-carbon/renewable energy use, fuel blending quotas, bans on internal combustion engines (ICEs) and fossil fuel boilers, energy/emission intensity reduction targets, public procurement of low-emission goods like cement and steel)
- **Funding** for investments, capital expenditure (e.g. soft loans, grants for equipment purchase, conversions)
- **Economic instruments** for operational expenditure (OPEX) guaranteeing revenue streams (e.g. contracts for difference (CfD), carbon contracts for difference (CCfD), feed-in tariffs, ownership benefits)
- **Mandatory disclosure** rules for information on nature impacts, GHG lifecycle emissions, and climate risks

6.2 THE POLICY TOOLBOX AT WORK IN ETO REGIONS

Below is a synopsis on the 'state of policy' in the ten ETO regions. More details on the application of the policy toolbox in the regions, with high-level summaries on supply and demand side policies, can be found in the standalone regional ETO reports.



High-income regions

- Europe (EUR)
- North America (NAM)
- OECD Pacific (OPA)

Middle-income regions

- Latin America (LAM)
- Middle East and North Africa (MEA)
- North East Eurasia (NEE)
- Greater China (CHN)
- South East Asia (SEA)

Low-income regions

- Sub-Saharan Africa (SSA)
- Indian Subcontinent (IND)

Policy toolbox

- Well-defined, proven measures
- Defined, partial results
- Early-stage, unclear results
- Insufficient, no results

Goals & Priorities 1	Fiscal 2
Technology-push 3	Demand-pull 4

HIGH-INCOME

Goals

EUR, OPA, and NAM [Canada] have plans for economy-wide decarbonization by mid-century. NAM [US] is dismantling federal-level climate policy.

Fiscal

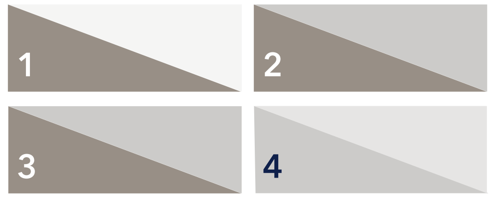
EUR and OPA evolve economy-wide carbon pricing (CP), and EUR non-compliance penalties, e.g. aviation blends. NAM [Canada] has industrial CP, NAM [US] lacks federal CP policy. Fossil-fuel subsidies remain in all regions.

Technology-push

EUR and OPA have extensive supply-side policy: funding to RD&D, technology, green supply chains, infrastructure investments, auctions, and CfDs to renewable (RE) power. NAM [US] cuts grants/loan programmes for clean energy demonstration; NAM [Canada] has funding to RD&D and tax incentives.

Demand-pull

EUR leads on binding RE targets across end-use sectors with funding tools. EUR and OPA incentivize hydrogen use (CCfDs), zero-emission transport, and industrial CCS. All regions have emission reduction/efficiency requirements. NAM [US] lacks federal, demand-side policy; NAM [Canada] and some US states enforce fossil-fuel heating bans, ICEs phase-outs, and RE obligations with deployment incentives.



MIDDLE-INCOME

Goals

CHN, dominated by China, maintains regulatory rigour and state-backed policy for decarbonization. Several regions balance entrenched fossil fuel interests with decarbonization.

Fiscal

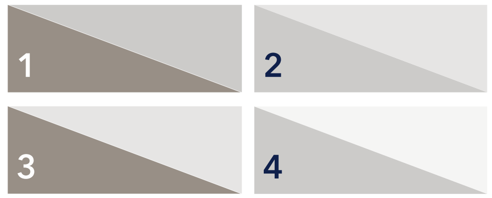
China is expanding its CP sector scope. Fiscal frameworks conducive to low-carbon development are evolving (MOF, 2022). CP in SEA is gaining traction, with Singapore leading the way. CP in other regions is immature. Fossil fuel subsidies remain widespread in all regions.

Technology-push

China is a frontrunner in innovation capacity, leading in RD&D funding and strategic industry/infrastructure investments. RE power, storage, and grids policy exist in most regions. MEA countries pursue CCS, hydrogen, and RE investments to diversify economies. Countries in SEA and LAM are evolving policy outside power (e.g. CCS, hydrogen, sustainable aviation fuels).

Demand-pull

China's policy framework encompasses orderly deployment measures, mandates, and emissions reduction/efficiency requirements. Beyond China, policy for end-use sectors is progressing somewhat slowly; Singapore is a notable exception in the SEA region.



LOW-INCOME

Goals

IND and SSA prioritize energy expansion plans for economic growth. Net-zero targets, mainly set for 2060-2070, are conditional on global support.

Fiscal

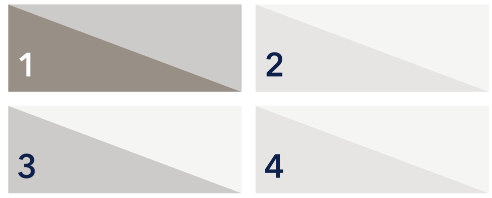
IND has India planning a carbon market by 2026, but overall, there is limited explicit CP. Both regions have ambitions to engage in global carbon markets (*Paris Agreement* Art. 6). Fossil-fuel subsidies remain widespread to ensure energy affordability.

Technology-push

India has national 'missions' and funding to deliver on technology development and manufacturing goals plus targets/support for RE generation and hydrogen production. Countries in SSA have a predominant RE power focus, some positioning for hydrogen export, and transition plans highlight financing needs instead of domestic funding.

Demand-pull

IND [India] has evolving policies, including energy savings, support schemes for e-mobility, renewable purchase obligations, and industry decarbonization. SSA policies predominantly focus on the power sector, with less progress in energy-demand sectors.



New NDCs and how we consider pledges in our analysis

In 2025, parties to the *Paris Agreement* need to submit their second nationally determined contributions (NDCs) for GHG emissions reduction through to 2035. These updated NDCs signal where countries plan to direct energy investments. In this context, the *New Collective Quantified Goal on Climate Finance* (NCQG), adopted at COP 29, was important for low- and middle-income countries to make their commitments, which will be heavily reliant on outside support.

As of 1 October 2025, only 56 of 180 countries with existing NDCs have submitted updated NDCs for 2035, covering 30% of global emissions (ClimateWatchData, 2025). Elsewhere (DNV, 2025 forthcoming), we contrast emissions related to our forecast with the average regional emission reduction targets and discuss overcoming the gap.

In our analysis, we monitor climate pledges and other announced government targets, but do not pre-set our ETO model to achieve them. At best, target announcements are initial steps in planning but depend entirely on real policies to back their realization. Most countries have inadequate short-term policies despite the boldest longer-term pledges. What matters for incorporation into DNV's analysis and modelling is that targets and plans are coupled with sectoral policy measures and aligned finance.

Select major NDC updates and reductions by 2035	
The UK	81% emissions reduction from 1990 levels
Brazil	59–67% emissions reduction from 2005 levels
Japan	60% emissions reduction from 2013 levels
The US	Abandoned the *Paris Agreement* and its 2050 net zero target

TABLE 6.1

The 2025 United Nations Climate Change Conference, COP 30, will be held in Belém, Brazil in November.

6.3 CARBON PRICE: ESSENTIAL BUT UNCERTAIN

Carbon pricing (CP) is the main market-based instrument that incentivizes CO_2 emissions reduction financially. To be effective, schemes must become increasingly stringent over time by limiting the volume of emissions, phasing out exemptions, and implementing the cost carbon sector wide. CP policies, like taxes and emissions trading systems (ETS), are evolving slowly in the global policy landscape. Our analysis shows that the increase in future carbon prices is slower than previous forecasts. However, it must be emphasized that CP is not the only tool available to encourage emissions reduction – some regions rely extensively on requirements and incentives to put a value on emissions reduction. Highlights on the 'state of play' from global expert reports, including those from the World Bank (2025) and the International Carbon Action Partnership (2025), include:

- 28% of global emissions are covered by carbon taxes or ETS
- 80 CP instruments have been implemented worldwide
- Most major economies have implemented CP or are considering it. Countries with implemented CP account for almost two-thirds of global GDP
- CP instruments raised over USD 100bn in revenue in 2024 for the second year in a row
- There are almost 1 billion tonnes of unretired carbon credits, as supply continues to exceed retirements

For our analysis, we derive a best estimate of the average regional CP trajectories to 2035, based on research into the policy trends and future CP levels in existing and expected schemes. From 2035 onwards, CP in the ETO Model is determined endogenously, based on regional emission intensity trends in the manufacturing and power sectors (Figure 6.2).

The massive difference in regional carbon pricing underscores why Europe – the leader in carbon pricing – needs its carbon border adjustment mechanism to level the economic playing field and preserve competitiveness.

Europe is the clear leader in carbon pricing

Carbon price in select regions (USD/tCO_2)

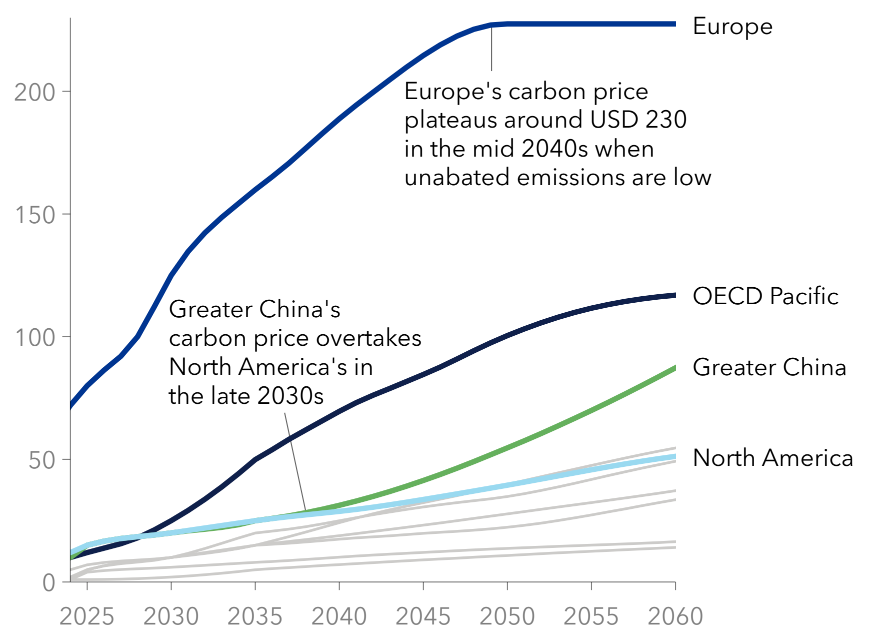


FIGURE 6.2 | All other world regions are shown in grey. Model calculation takes over estimates from 2035.

Europe
- Europe is the clear leader in CP policy. We expect ETS-1 to tighten the supply of allowances in the late 2020s or early 2030s, resulting in higher CP. The industrial sector becoming the primary emitter within the ETS will also contribute.
- ETS-1 covers 45% of emissions and the introduction of ETS-2 brings coverage to 78% of total emissions. ETS is supplemented by national taxes.

OECD Pacific
- CP mechanisms are in place in all countries, but currently have limited impact due to several factors: CP covers a limited share of emissions (Japan); free allowances cover all or almost all emissions (South Korea, future Japan ETS); and emission benchmarks are high enough that almost no installation pays CP (Australia). As a result, the effective CP is currently low.

Greater China
- By 2025, China's national ETS will expand to cover steel, cement, and aluminium smelting industries that account for 60% of national emissions. Further coverage of all industry sectors and aviation is expected by 2027. From current modest levels, an absolute cap by 2030 will likely drive prices upwards.
- CBAM is a driver for China's ETS expansion, given China's significant exports to Europe.

Latin America
- Major economies (Brazil and Mexico) have made steps to implement ETS while Chile and Columbia may transition existing instruments. Pricing remains particularly low where mechanisms are limited or absent (Argentina and Venezuela).
- Free allocation and offset mechanisms remain critical factors keeping the effective CP below potential market prices in the near to medium term across the region.

North America
- Canada has removed the requirement for provinces and territories to have a consumer-facing CP in place. Industrial CP remains with an annually increasing national price trajectory but gives flexibility in the type of system implemented.
- In the US, CP is determined at the state level. Despite uncertainty following the new administration, the existing CP schemes in 12 states are continuing.

South East Asia
- Established policies include Indonesia's ETS, which has expansions planned in the coming years, and Singapore's carbon tax, which covers 70% of national emissions.
- ETS are in development for Vietnam and Thailand, and under consideration in Malaysia and the Philippines.
- There is some nascent interest in a regionwide ETS.

Middle East and North Africa
- We expect the transition to effective CP to evolve as voluntary markets mature and governments consider more binding mechanisms in the medium to long term.
- Motivated by EU CBAM, Turkey is a frontrunner with its ETS planned to cover 44% of emissions (energy and manufacturing) starting in 2026.

Indian Subcontinent
- India's carbon credit trading scheme will cover 16% of emissions in the energy-intensive industrial sector. Power is not included, but is planned for a later stage.
- There is significant uncertainty about using voluntary offset credits in India's compliance market.
- Pakistan will introduce a carbon tax on high-emission industry, with an ETS by 2030 under discussion.

North East Eurasia
- CP adoption is slow across the whole region, with no development outside the two existing schemes. Kazakhstan's scheme covers 44% of emissions and Ukraine has a carbon tax and plans for an ETS. Prices in both countries remain low.

Sub-Saharan Africa
- South Africa has the only implemented carbon tax in the region.
- CP policies are under consideration in Senegal, Cote d'Ivoire, Botswana, and Kenya, and Nigeria has announced an ETS.
- The Congo Basin is a key asset in the global carbon credit market.

Regional summary ordered by descending 2060 carbon price level.

6.4 THE EFFECT OF POLICY ON HYDROGEN DEVELOPMENT

In this section, we highlight the 'state of play' in global hydrogen policy and use select regions to illustrate how policy influences the Outlook.

Despite a renewed push for hydrogen starting around 2020, multiple factors have caused delays and deployment is taking longer than expected. Some argue that hydrogen is in the 'valley of death or despair' (Hydrogen Summit 2025) where entrepreneurs struggle to keep afloat until commercial scaling is achieved. Both industry and policymakers now have a more nuanced understanding of value chain complexity and the substantial scaling that still lies ahead for the nascent industry and the ongoing need for governance and enabling policies.

Low-emission hydrogen is and will remain significantly more expensive than the unabated, fossil-based alternative. Government funding programmes help to narrow this disparity through investment grants or loans (CAPEX support) or through production subsidies (OPEX support) to make projects investible. Increasingly common CfDs work on both the producer and user side: they guarantee a minimum price to encourage production and provide a price hedge against fossil-fuel prices to reduce the cost of using hydrogen.

Policies heavily influence competitiveness of hydrogen production routes

Levelized cost of hydrogen (USD/kg)

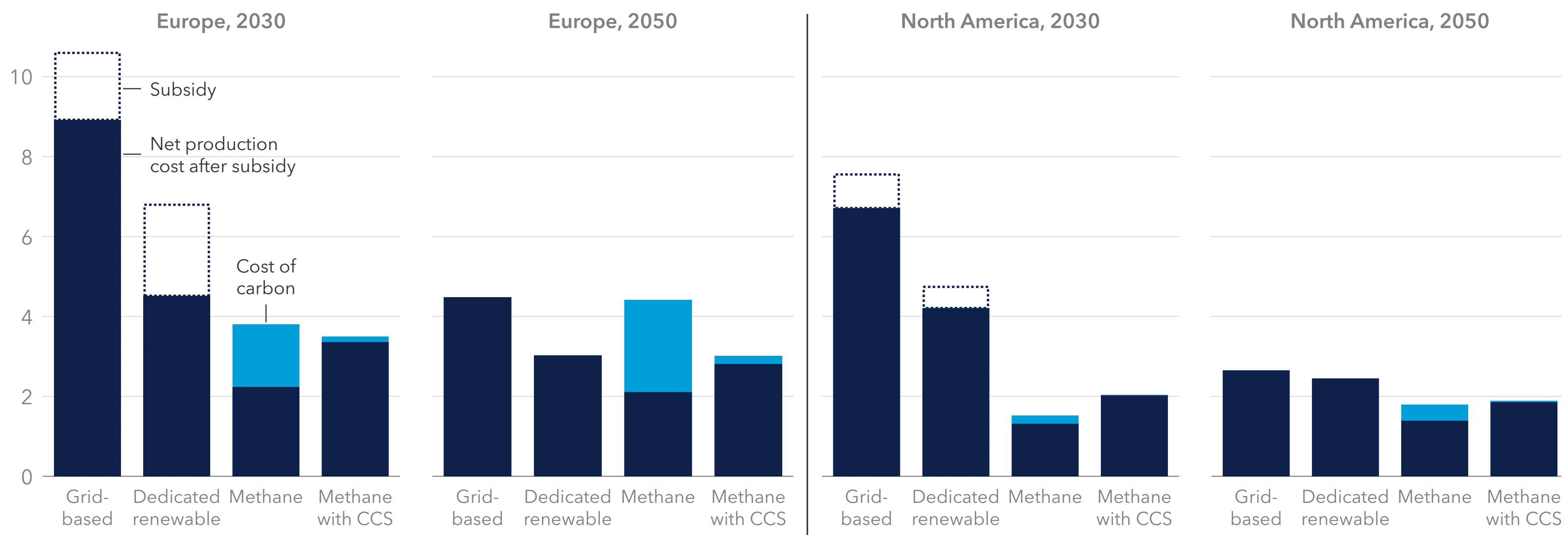


FIGURE 6.3 | The subsidy reflects average support levels across the qualified projects, taking into account that projects may receive either CAPEX or OPEX support, or in some cases both.

Key policy highlights

- Supply-side measures with government funding to catalyse investments in production capacity have staying power, but developments are evolving slower than targets (e.g. REPowerEU).
- Varying CO_2-eq/kgH_2 thresholds (below fossil-fuel benchmarks) in support schemes for hydrogen and derivatives add complexity. Industry scaling and global trade would benefit from regulatory alignment and standardized GHG accounting methodology.
- Demand-side measures like end-use targets, mandates, public procurement of low-emission goods like cement and steel, and CfD/CCfDs are emerging, but only in a few regions. These will likely expand to advance offtake certainty and value chain development.
- Carbon pricing will be essential to help narrow the cost gap with conventional hydrogen.

Illustrating the policy impact on the cost competitiveness of production routes

The policy aspects accounted for in our forecast reflect that projects in many regions receive both OPEX and CAPEX support in supply and demand sectors and competition is also affected by the regional carbon price. We will illustrate this using two ETO regions: Europe and North America.

Europe's policy framework is comprehensive. *REPowerEU* goals prioritize renewable hydrogen under *RED III* and Delegated Acts to reduce import dependency. To enhance production capacity, support includes the European Hydrogen Bank's (EHB) competitive auctions fixing EUR/kg premiums to certified renewable H_2. EHB's auctions-as-a-service enable national auctions, and H_2 Global facilitates import auctions. Measures to establish demand include CCfDs to incentivize industrial H_2 use and *RED III* mandating RFNBO use in industry, although uneven national implementation is a significant challenge that creates offtake uncertainty. European support for renewable-based hydrogen drives the initial uptake which leads to reduction in costs in 2050 (Figure 6.3). Grid-connected has initial high cost due to the higher CO_2 emission intensity of the grid adding a cost premium to source renewable electricity (PPAs), but costs come down as the grid's emission intensity declines with renewables penetration. In North America, with the US being the dominant economy, the preserved US 45-Q tax credit to carbon capture results in predominant regional natural gas-based hydrogen focus, and low-carbon hydrogen is brought closer to unabated production costs.

Note: Innovation Fund IF25 Hydrogen Auction Draft Terms and Conditions 30 July 2025. are not reflected in this year's Outlook.

Demand-side measures and carbon pricing will be essential to reinforce offtake and narrow the cost gap.

7 FINANCING THE ENERGY TRANSITION

7.0 HIGHLIGHTS

Re-evaluating risks: balancing short-term shocks with long-term fundamentals

- While policy uncertainty in some nations may pose immediate risks for green investments, the fundamental long-term drivers of the transition remain firmly intact. The superior economics of mature renewables and the strength of domestic renewables satisfy the strategic need for energy security.
- While the risk of a 'negative spiral' threatens emerging energy technologies today, the long-term momentum is unstoppable. Fading subsidies and higher capital costs create significant short-term hurdles for projects like clean hydrogen and floating offshore wind, but the powerful underlying dynamic of technology cost learning curves ensures that the costs of these technologies will continue to fall and their role in the transition will grow.

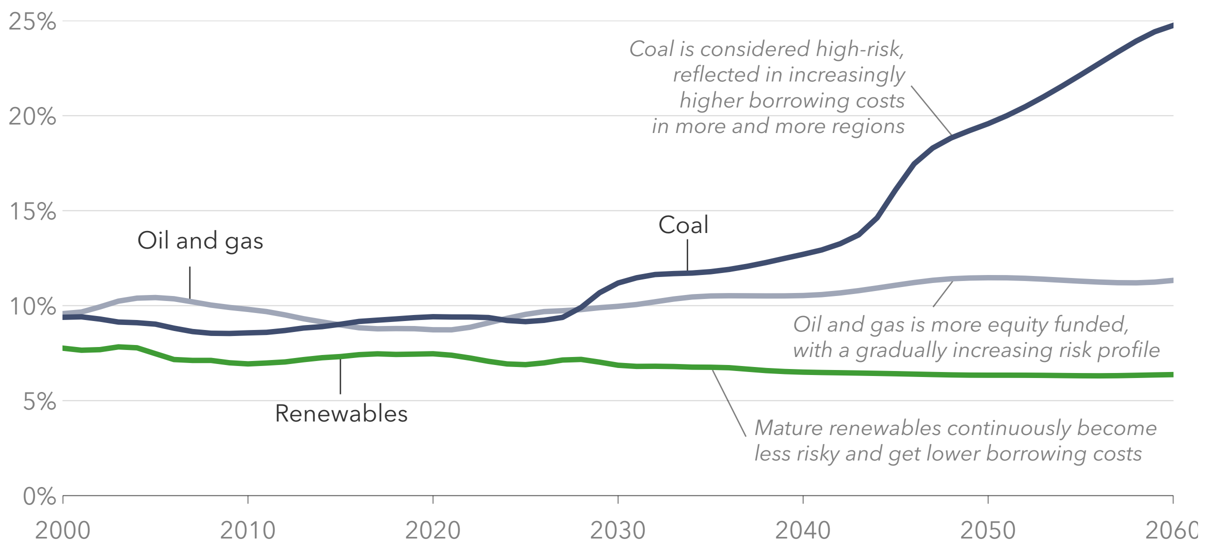
From extraction to electricity: the financial transition

- Our forecast shows a massive redirection of capital from fossil fuel extraction to an electrified world of power generation, grids, and energy storage.
- In line with this shift, investment in the electrical grid is set to double by 2050, and spending on power storage will triple by 2040 to support the surge in intermittent renewables. In contrast, investment in fossil fuel extraction will fall to USD 500bn per year by 2050, less than a quarter of current levels.
- While capital investment in new renewables is booming, a look at total expenditures (including operational costs) provides a more complete picture. Although, GDP will double, total global energy expenditures remain relatively flat at around USD 6.5trn throughout our forecast period. Rising electrification means that the energy intensity of the global economy falls as the transition advances, i.e. it will take progressively less energy to produce one unit of economic output.

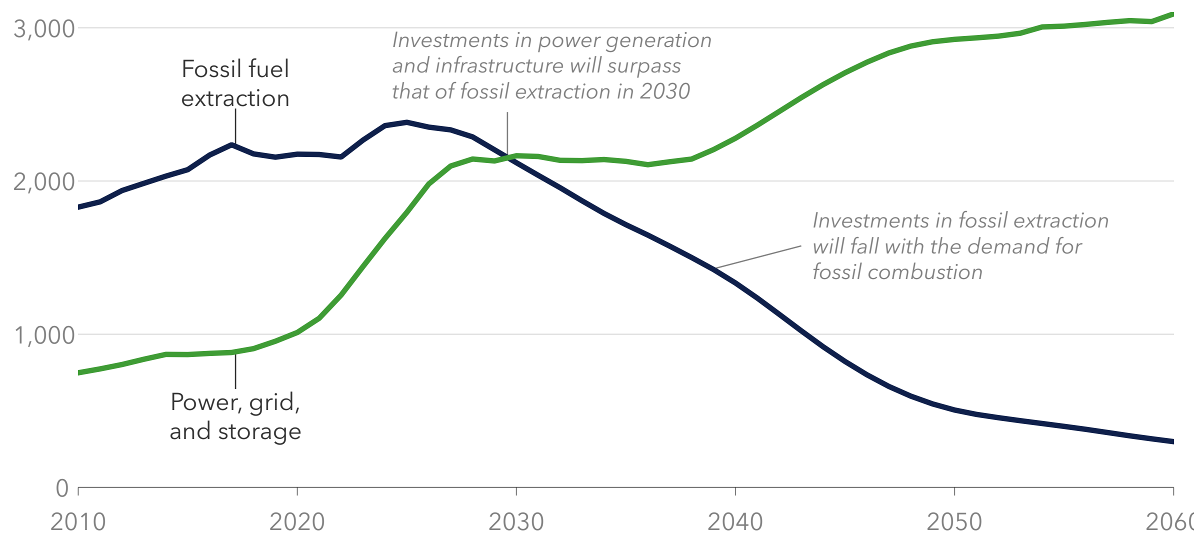
Renewable investment everywhere; fossil concentration

- Greater China is by far the leading region for renewables investment, driven by state-owned banks financing projects to serve national energy security interests. While the pace of new additions may slow in the 2030s, China will maintain its position at the forefront of investment in solar and wind through our forecast period.
- In stark contrast to present political developments and world-leading oil and gas production capabilities, it is likely North America's private capital markets will fuel a dramatic pivot to renewables with superior economics in the 2030s. This pivot will see oil and gas investment decline by 70% in the 2030s compared with the 2020s and position North America as the second-largest region for renewables investment.
- Over time, oil and gas investment will be increasingly concentrated in self-financed, low-cost regions, principally the Middle East and North Africa. North East Eurasia will also stand out as the primary investor in its own upstream assets.

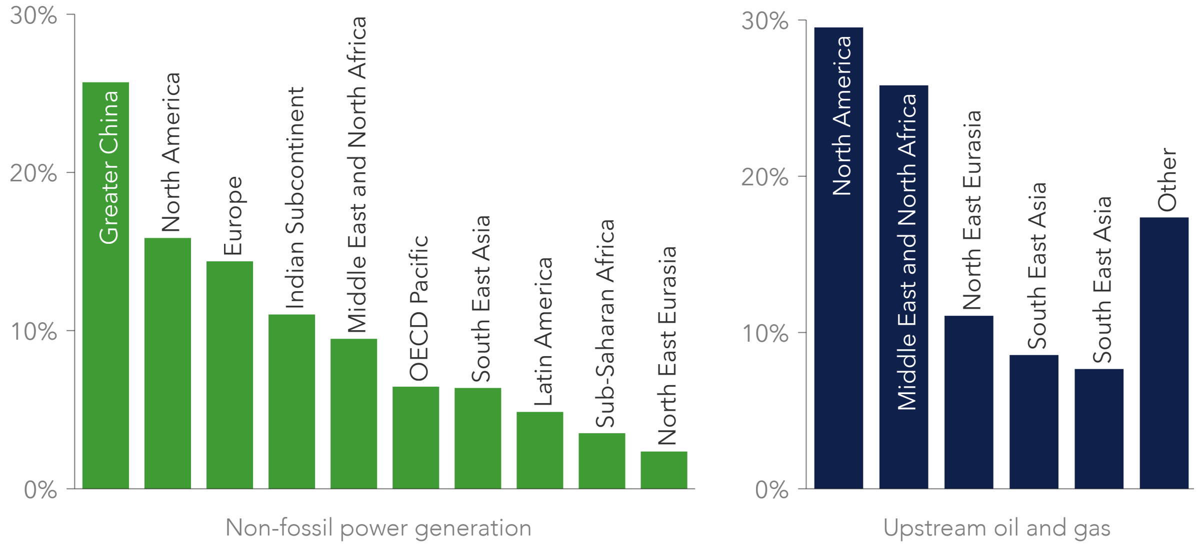
Global weighted average yearly cost of capital for new investments



Total investments (Billion USD/yr)



Share of energy investment by region, 2025–2060



7.1 THE INVESTMENT TRANSITION – FROM FOSSIL FUELS TO ELECTRICITY INFRASTRUCTURE

Energy expenditures are set to plateau

Energy expenditures are the costs related to the production of energy and its transport to the user, including operational expenditure (OPEX) and capital expenditure (CAPEX). While global energy expenditures have grown 50% since 2010, in line with global GDP, that correlation is now starting to unravel. While progressively less is expended each year in the fossil fuel energy system and more is spent on building and running non-fossil power and grids, overall energy expenditure does not rise dramatically (Figure 7.1). Indeed, the average annual expenditure on energy around 2050 will be USD 6.5trn, no larger than today's levels, while GDP will have almost doubled.

Total energy expenditures will plateau in the 2030s
World energy expenditures (Billion USD/yr)

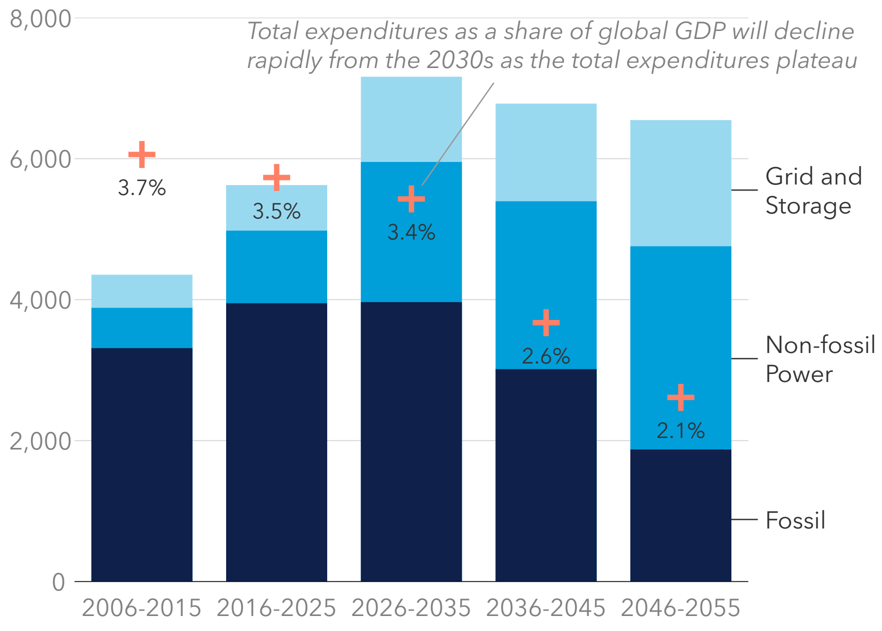


FIGURE 7.1 | Fossil includes upstream, midstream, and power generation.

That energy expenditure becomes an ever-smaller proportion of global GDP during our forecast period is testament to the very low OPEX of the dominant technologies in the mid-century energy mix and the vast efficiencies enabled by electrification (see Chapter 2 for further discussion). This pattern will likely be mirrored at a micro level in most households. As prosperity increases and efficient electrification of end uses deepens, we expect energy costs to comprise an ever-smaller proportion of household expenditures.

The rise and fall of fossil investments

Fossil fuel demand has grown steadily since the 19th century. The prospect of falling demand setting in before 2030 – a high likelihood given the ongoing electrification of transport and heating and rising carbon costs – is new territory for investors. The implication for the fossil fuel industry is reduced investments in new fields, geographic concentration of production, and falling operational expenditures from the early 2030s.

The timing of the transition will differ across regions. For example, most regions are moving away from coal fired power generation, but some are still prioritizing coal for firm capacity or energy security. Coal production will increase by 46% across the Indian Subcontinent by 2039 to meet its growing energy demand.

Variable and firm power generation

Investments in solar (including storage) rose from USD 110bn in 2014 to USD 570bn in 2024, and will grow to USD 900bn by 2044. Wind power saw a tripling in investment over the last decade to USD 180bn, and is set to triple again by 2044 (Figure 7.2). As these two sources begin to dominate electrical power supply, substantial investments in energy storage and flexibility will be made, not least in firming capacity that can generate power on demand. This includes other renewables, nuclear, and fossil power. These sources will deliver power for the relatively rare time periods when variable+storage proves insufficient, supporting the grid when necessary at higher capture prices. Firm power generation will continue to attract USD 350bn on average in investment annually through to 2050.

Grid and storage

Investments in energy storage, such as batteries and pumped hydro storage, have grown seven-fold over the last decade to USD 50bn/yr. Going forward, ever more solar farms will be built with battery storage included, attracting as much investment as standalone solar PV in 2029. The combined storage investments will reach USD 150bn/yr in the 2030s and USD 300bn/yr in the 2050s.

Even though the grid buildout lags the renewables buildout, investments in the grid will double by mid-century (see discussion below and in Section 3.6).

More and more global energy investments will be concentrated in wind, solar, and grids
World CAPEX by technology (Billion USD/yr)

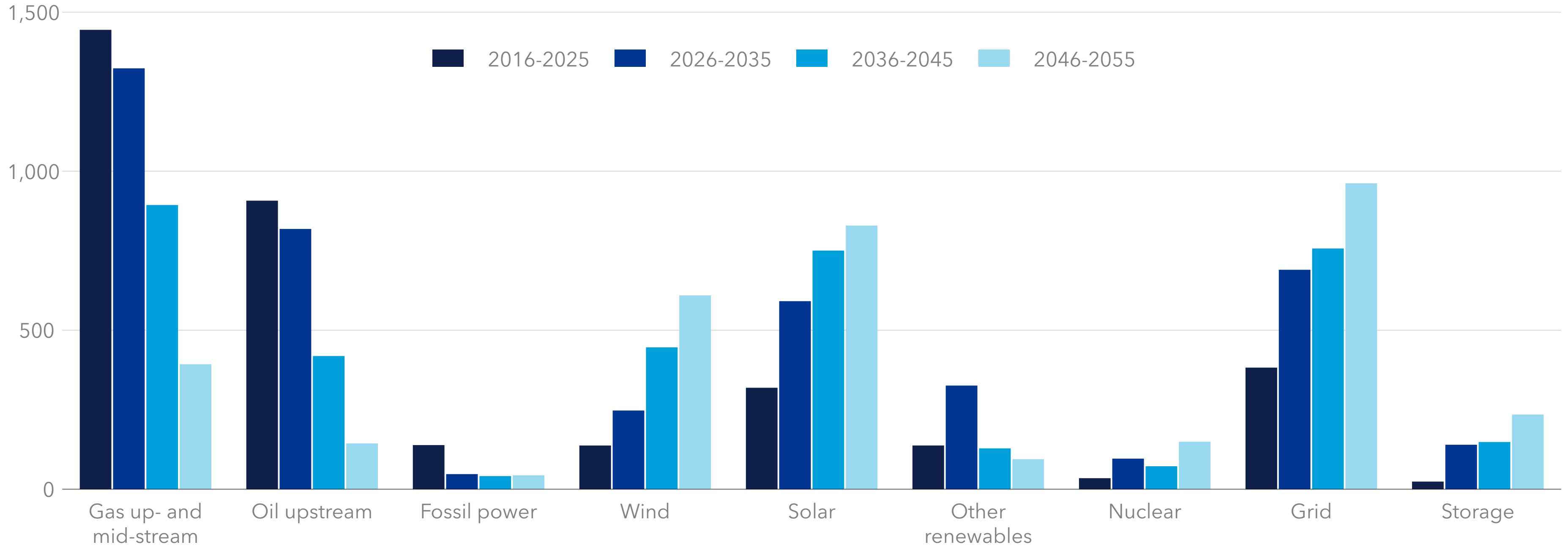


FIGURE 7.2 | Historical data source: DNV analysis

7.2 DIVERGING FINANCIAL LANDSCAPE – MAPPING THE NEW REALITIES OF ENERGY INVESTMENT

The years of abundant, low-cost capital have been abruptly replaced by a more complicated and fragmented risk picture.

The energy transition towards 2060 was never thought to be a steady journey to net zero, but recent headwinds are making the journey decidedly turbulent.

Geopolitical shocks are sending ripple effects through the finance community and fundamentally altering the risk landscape. In several countries, risks related to green investments have increased, while their returns are under pressure. The opposite appears to be true for the oil and gas industry in the US.

So, what do these short-term headwinds mean for how we predict financing will be allocated to new energy expenditures? Our contention is that access to capital and its cost are now dictated by a region's unique response to these pressures, its approach to energy security, and its existing economic structure.

High-income transition leaders: the dominance of private capital
While historically grouped together, Europe and North America are taking increasingly divergent paths in financing the energy transition. Both operate within mature financial markets, but their blend of policy, private-sector commitment, and political will is creating two distinct investment landscapes.

Europe: Policy-driven green investments
Europe is taking a regulated, top-down approach to financing energy investments. Its mature debt and equity markets are being systematically steered by strong policy signals for decarbonization and clean energy priorities. This policy-driven environment provides a clear long-term trajectory for investors.

However, this policy push is now somewhat constrained by a new geopolitical dilemma. Europe's historic dependence on Russia for its energy supply, and on China for its manufacturing capacity of solar PV and batteries, has made the region vulnerable. There are no quick fixes; a fast transition and electrification would mean an increased dependence on China-dominated value chains. In response, investors and European governments now need to balance their exposure. One way of doing this is to source fossil fuels from regions other than Russia, a move that complicates the immediate path to decarbonization.

Funding profile & drivers: European energy investments are funded by a combination of private equity and commercial debt, supported by a clear political and regulatory consensus. The financial sector's alignment with decarbonization is reinforced by strong, continent-wide initiatives (Plé, 2025). Alliances like the UN's Net-Zero Banking Alliance have a significant influence here, embedding green objectives into the core of financial operations. This creates a powerful mechanism for directing capital away from fossil fuels and towards renewables.

Resulting costs: The consistent policy direction helps lower perceived risk for green investments. While all regions have faced higher borrowing costs due to recent inflation, the strong regulatory framework in Europe provides a degree of stability. This makes it a more favourable environment for capital-intensive, less mature technologies like clean hydrogen and floating offshore wind that depend on long-term policy certainty to be viable.

North America: A fractured & market-driven landscape
In North America, particularly the US, the path is less uniform and more reliant on market forces and fluctuating political winds. While possessing the world's deepest capital markets, the commitment to the energy transition is fractured.

Funding profile & drivers: The funding mix is similar to Europe's, relying on private enterprises, households, and debt from financial institutions. However, it is heavily influenced by specific incentives like government tax credits, and their recission, rather than overarching regulation. The result is the lack of consistent commitment from the private sector. The influence of initiatives like the Net-Zero Banking Alliance is waning. Several major US banks have recently abandoned their net-zero commitments, creating uncertainty and a less predictable environment for financing the transition.

Resulting costs: This inconsistency can increase perceived risk and capital costs. While mature technologies like solar and onshore wind remain competitive due to their strong economics, weak support from key financial players creates headwinds. For investors in emerging technologies, this translates into higher uncertainty about the long-term availability of capital. This may increase the cost of capital and make projects more dependent on short-term policy incentives rather than a stable, long-term market framework.

Shared outcomes for legacy and mature technologies
Despite this divergence, some outcomes remain consistent across the Atlantic. In both Europe and North America:

- Coal is perceived by investors as a significantly high-risk asset, reflected in increasingly punitive borrowing costs over the past decade.
- Mature renewables like onshore wind and utility-scale solar PV are, in most instances, the cheapest and most attractive option for new power generation due to their proven commercial viability.
- Oil and gas investments are now generally seen as riskier than mature renewables, resulting in a higher cost of capital for new projects in these regions.

State-led & resource-rich economies: capital as a tool of national policy
In sharp contrast to Europe and North America, regions with large state influence or abundant fossil fuel resources operate under a very different financing paradigm.

Funding profile & cost drivers
Regions with large oil and gas production, like North East Eurasia and the Middle East and North Africa, see less dependence on bank financing. Their energy investments are largely financed by the immense cash flow from operating activities. Here, oil and gas prices are the primary drivers of capital access for new fossil energy investments.

In Greater China and the Indian Subcontinent, state-owned firms dominate the energy sector, and public financing dictates the pace and direction of investment. Most coal-fired power is state-owned, funded with equity from public entities and debt from state-backed banks offering favourable terms. These investments serve national priorities: ensuring baseload power, enhancing energy security, and reducing the influence of geopolitical factors.

For India, the strategy is more complex than simply supporting all domestic energy sources equally. While locally-mined coal continues to receive favourable financing, PV expansion is a serious effort to wean itself off expensive and geopolitically sensitive coal imports (Sharma, 2025). In this context, renewables are not just a parallel path to coal, but a direct tool to enhance energy security by reducing exposure to international markets.

This state-led model is also insulated from global inflationary pressures. After lowering interest rates in 2023, China's central bank has not changed its steering rates. With consumer prices rising slowly, borrowing costs in this region are not affected by the high-interest-rate environment seen elsewhere.

Resulting costs by technology

- Oil and gas (Middle East and North Africa): The region contains the world's lowest-cost oil and gas producers. Consequently, investments there are rewarded with attractive financing terms and a low cost of capital, a risk perception we expect to last over the full forecast period to 2060.

- Coal (Greater China and the Indian Subcontinent): These regions have continued access to generous sources of liquidity for coal (White, 2025). Although financiers are changing, state backing ensures attractive financing. We expect ample access to capital, and thereby low risk premiums, for new coal-fired generation through 2030 in Greater China and 2040 in the Indian Subcontinent, after which risk premiums will rise rapidly.

Low-income, high-risk regions: navigating a precarious, new landscape
For many low-income regions, particularly in Sub-Saharan Africa, the primary challenge is a large funding gap to meet investment needs in new electricity generation. The investment environment is defined by high-risk premiums driven by a combination of economic, political, and institutional factors. These consist of political and security risks, sovereign credit risks, currency risks, and energy system risks, all of which deter private capital.

This already challenging environment is being exacerbated by significant shifts from the region's key international financing partners. Things are trending worse for Sub-Saharan Africa in the short term. The US has recently rapidly withdrawn 'soft power,' scaling back commitments to initiatives like Power Africa and the Just Energy Transition Partnerships. China's changing stance is less recognized, but equally important. Its once-significant energy financing in Africa is evolving, moving away from developmental aid towards a more 'commercial' approach (Tianyi, 2025). This leaves many African nations navigating a more commercially driven, and precarious, financing environment.

Funding profile & cost drivers
The retreat of concessional finance from these major partners forces a greater reliance on an already complex and often expensive mix of capital. Available funding comes from a patchwork of commercial and public finance, with less than 20% of total energy investment financed through development finance institutions. The financing structures vary widely. In South Africa, most renewable energy projects are predominantly financed through debt in local currency, whereas in Senegal, Malawi, and Botswana, concessional finance and equity play a more significant role. The overarching driver for the cost of this capital remains high risk, and can only be partially mitigated by measures like legally binding power purchase agreements and sovereign guarantees (Koefoed, 2025).

Resulting costs & opportunities by technology
This precarious new reality sharpens the divide between different types of energy projects and their viability.

- Large-scale projects: The investment case for large-scale energy projects, which rely on government contracts, remains exceptionally challenging. With traditional state-to-state financing becoming less certain, they face increased vulnerability to the region's high-risk profile.

- Small-scale solar: The role of decentralized power becomes paramount. Small-scale solar is less susceptible to the political instability and high-level financing risks that plague larger projects. Its unique scalability allows it to be funded by a wider range of investors, including households, bypassing some of the hurdles that deter major international financiers.

Conclusion: short-term volatility, long-term trajectory
The current energy financing landscape is undeniably volatile. However, to mistake these turbulent crosscurrents for a greater sea change would be misreading the deeper, structural forces at play.

Despite some policy backsliding, mainly in the US, the overall direction of travel remains overwhelmingly in favour of the energy transition. The fundamental drivers are now so deeply embedded that they transcend short-term politics and market disruptions. The superior economics of mature renewables, the strategic imperative for energy security, and the unstoppable momentum of technological maturity form a powerful, self-reinforcing engine for change. The challenges detailed in this report are significant, but they represent a period of risk and cost recalibration, not a reversal of the entire transition.

Solid principles driving the transition

While regional realities create distinct financing environments, several overarching themes hold true across the world that define the global picture of energy finance.

The inescapable link between maturity and cost

The installed capacity of any given technology typically increases along an S-shaped transition curve. With expanding buildout, risks reduce, business cases mature, and the perception of risk falls, resulting in lower borrowing costs and a lower cost of capital (CoC). This is why immature technologies like floating offshore wind and clean hydrogen – where scale deployment has yet to take root – have a CoC roughly 5% higher than mature ones (Figure 7.3).

Grids and pipelines: the foundational layer

In regions committed to modernizing or expanding energy infrastructure, we expect CoC to remain relatively low and stable, with inflationary effects gradually diminishing towards 2030. Despite these favourable conditions, investment in grids is currently lagging. There is a real bottleneck that requires innovative financial structures and market models to solve (Cordonnier, 2025).

Government involvement will be significant, especially where investments align with decarbonization goals, energy security, and system resilience. Public funding, guarantees, and regulated returns will play a central role in de-risking projects. Towards 2050, we expect conditions for energy infrastructure to be relatively consistent, with limited variation in CoC across comparable regions. The main differences are attributed to country and region risks.

Stability for state-backed nuclear

In regions willing to sustain or expand nuclear power, we expect CoC to be low and stable over time with inflationary impacts tapering off towards 2030. Government intervention will be substantial in most regions, with regulated returns. Public funding and government support will be available, motivated by energy security, safeguarding knowledge in nuclear technology, and shielding investors from some of the safety-concern risks. Towards 2050, we do not expect large deviations.

The special case of solar PV

No other technology has Solar PV's scalability potential. The ability to deploy the same basic product on a residential roof or in a multi-gigawatt desert project allows it to tap into a uniquely diverse investor base. The large share of investments made by households in solar PV lowers overall financing hurdles and improves access to capital compared to other technologies, despite inefficiencies (Figure 7.4). This adaptability makes solar a resilient and crucial technology in every financing environment, from the private markets of the West to the developing economies of Africa and Asia.

Speed will differ between regions, but renewables will constantly benefit from lower cost of capital

Average regional yearly cost of capital by technology

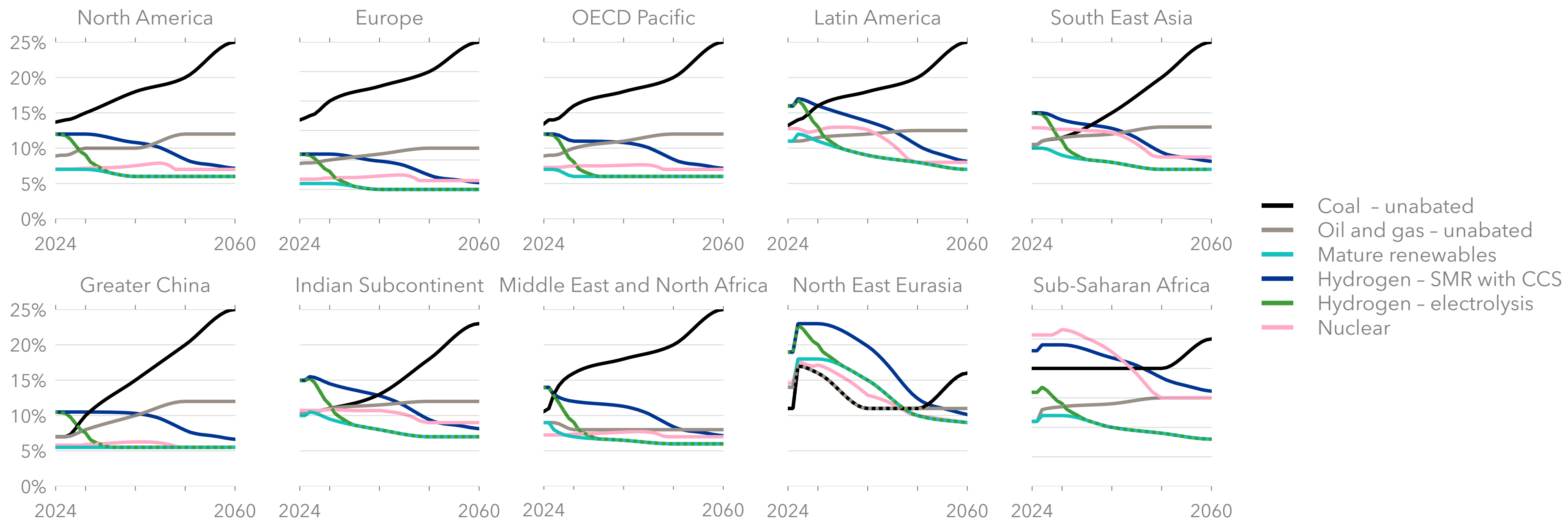


FIGURE 7.3 | CoC is a composite of three elements: 1) The cost of debt - the combination of the risk-free rate and the risk premium, or margin, together often referred to as borrowing costs, 2) the cost of equity - the return required by investors, and 3) the debt-to-equity ratio - often referred to as 'leverage'.

Only 70% of global solar investments will go to utility-scale through 2060

World solar CAPEX by end use (Billion USD/yr)

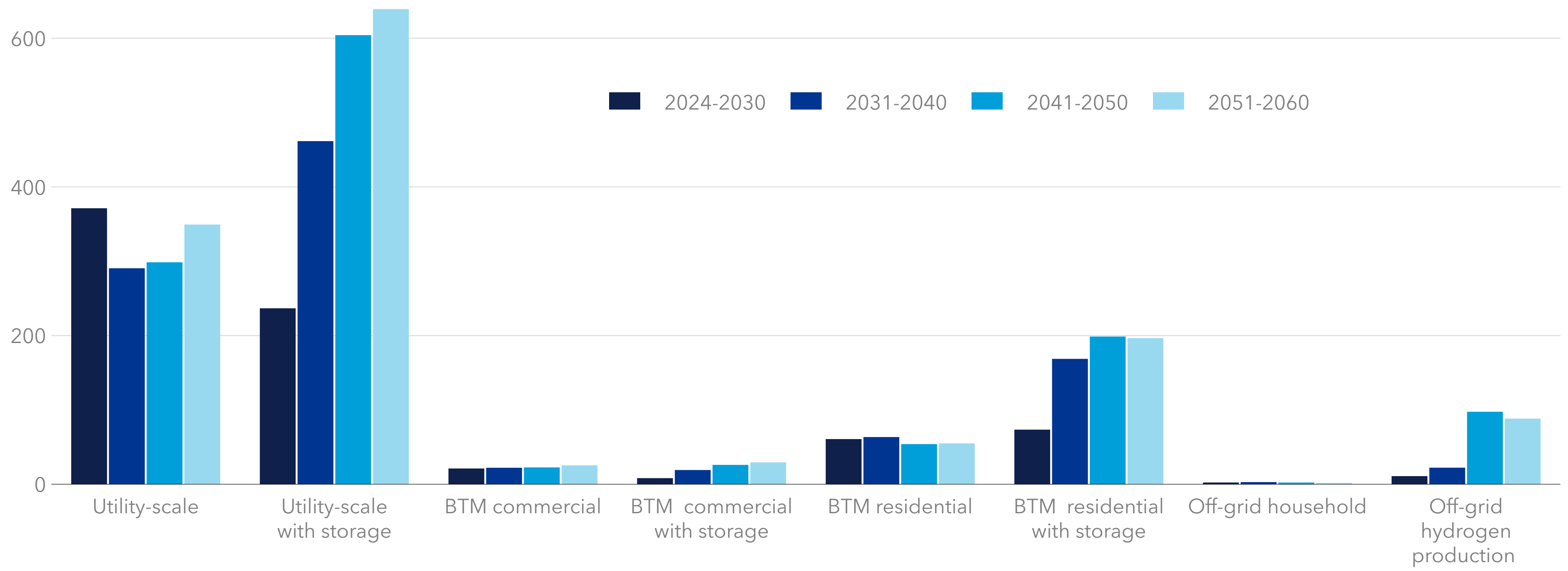
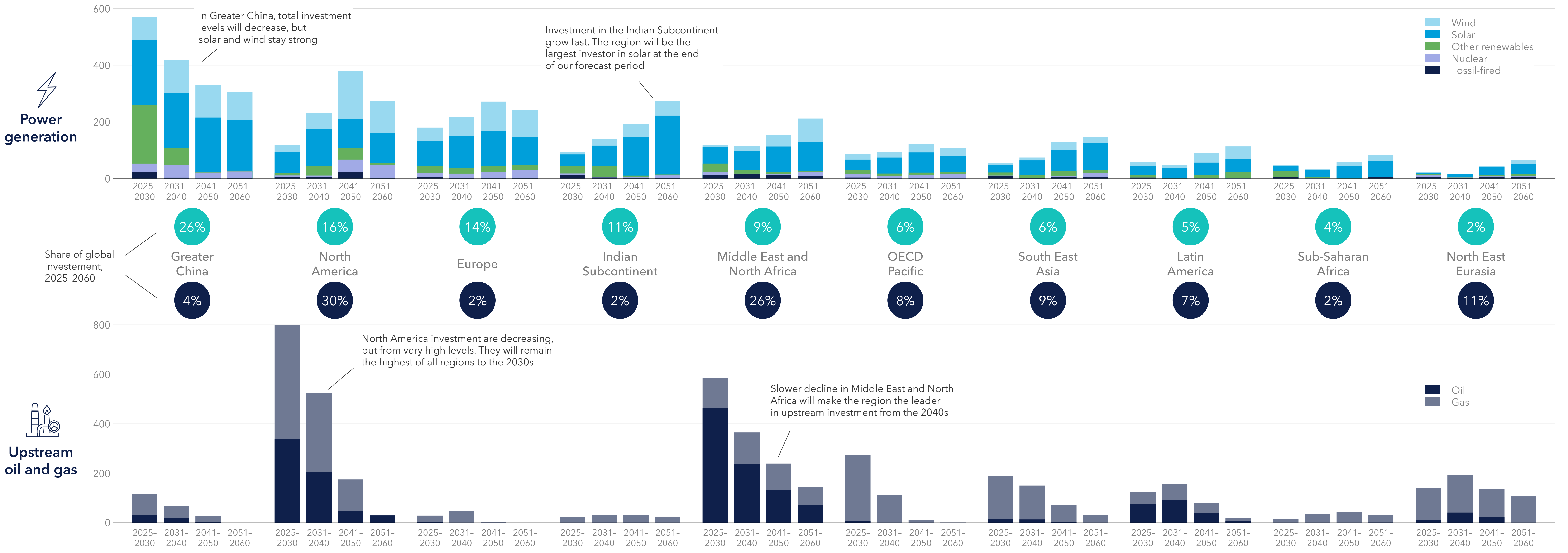


FIGURE 7.4 | BTM: Behind-the-meter

7.3 THE REGIONAL PICTURE FOR ENERGY INVESTMENTS

Renewable investment will be spread out in all regions, with different technology choices

Average yearly investment by region (Billion USD/yr)



8 EMISSIONS AND CLIMATE IMPLICATIONS

8.0 HIGHLIGHTS

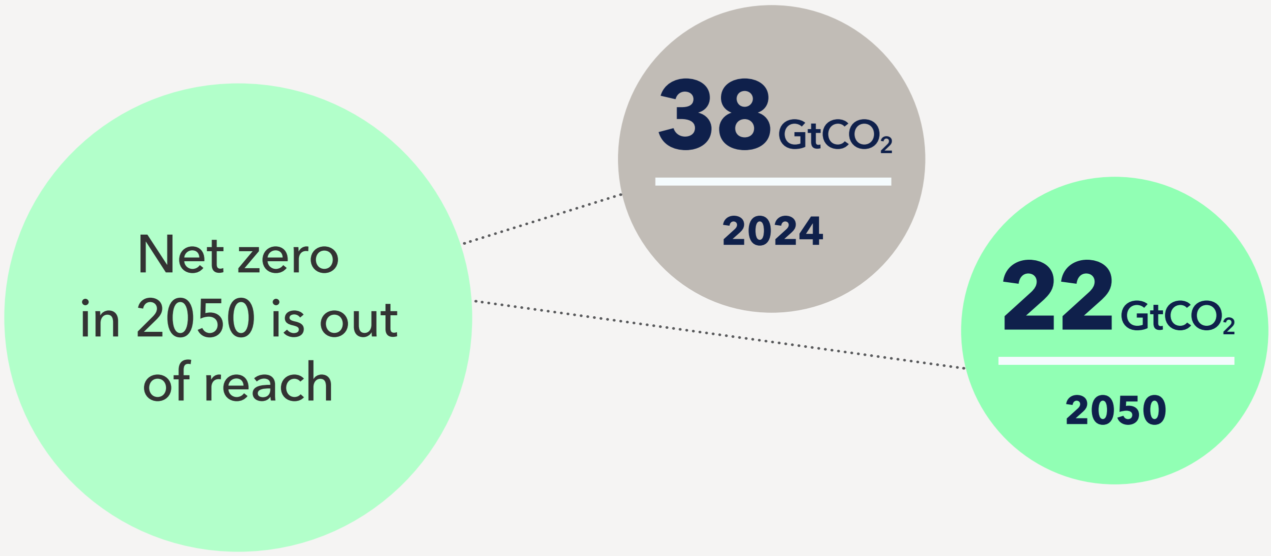
Emissions – Energy-related CO_2 peaks and begins a slow decline from 2026. Emissions nearly halve by mid-century due to electrification, increased uptake of renewables, and some point-source carbon capture and storage (CCS).

Sector shift – The power sector decarbonizes fastest as wind and solar dominate new capacity additions. By 2060, transport becomes the largest source of emissions, primarily from aviation and shipping.

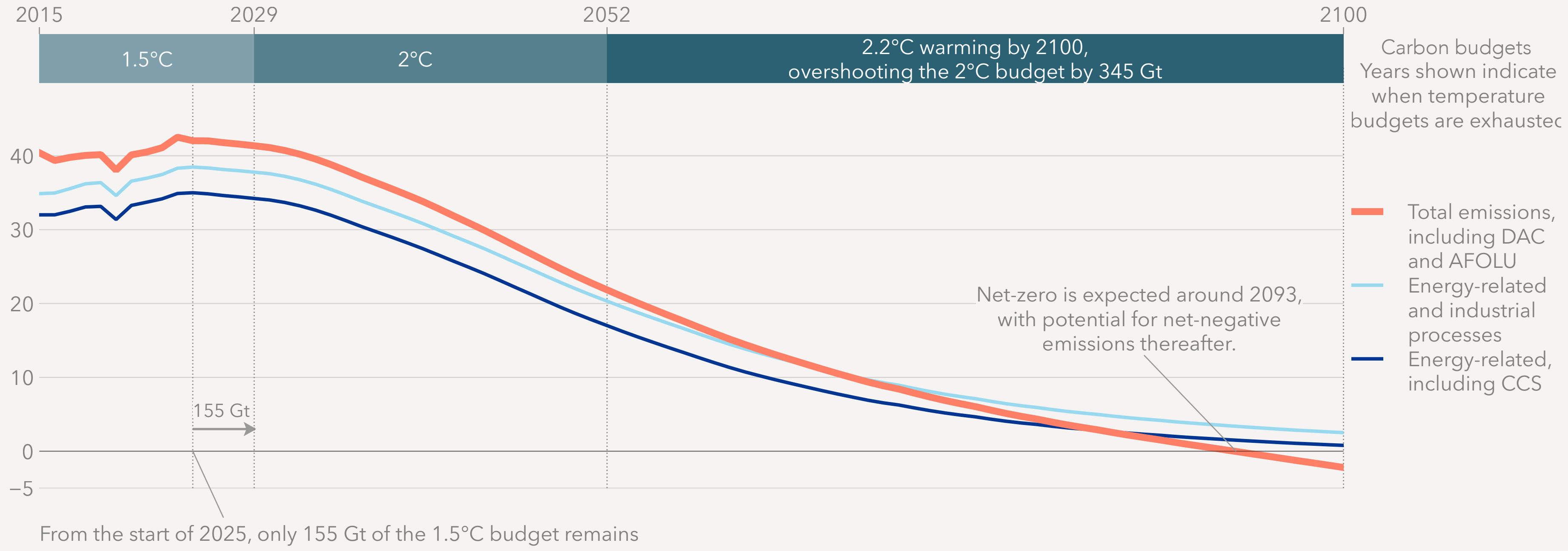
Regional divergence – Emissions trajectories diverge. Europe reaches net zero by 2060. North America and OECD Pacific make deep cuts, but fail to reach net zero. Greater China peaks around 2030 then declines quickly. The Indian Sub-continent peaks later and falls moderately. Sub-Saharan Africa's emissions rise from a low base.

Carbon budget and global warming – We forecast the 1.5°C carbon budget threshold will exhaust by 2029 and the 2.0°C budget by 2052. Extending the forecast pathway to 2100 with modest removals implies net zero CO_2 in the early-2090s, resulting in 2.2°C warming by the end of the century.

Net zero in 2050 is out of reach – All IPCC scenarios which limit temperature rise to 1.5°C require achieving net zero by 2050 (IPCC, 2023). However, we now forecast CO_2 emissions will be 22 Gt in 2050. This gap is unbridgeable in any reasonable sense. Still, achieving net zero as early as possible remains critical; every tenth of a degree of warming brings exponentially greater harm to our planet and costs to society.



World CO_2 emissions ($GtCO_2$) and associated carbon budgets



DNV Energy Transition Outlook temperature estimates use the IPCC Sixth Assessment Report (AR6) carbon budgets.

8.1 EMISSIONS

Global energy-related CO_2 emissions have continued to rise since the temporary dip during the COVID-19 pandemic. We expect this upward trend to become a steady decline in 2026 that results in emissions halving by the end of the century. The reduction will be driven by significant growth in renewable energy, efficiencies (mainly related to electrification), and advances in CO_2 capture and removal.

Energy-related CO_2 emissions have historically grown in line with GDP and population increase. Between 2014 and 2018, that pattern broke as emissions plateaued while global economic growth continued. In 2020, emissions dipped in line with the COVID-19 slowdown. They have since started growing again, albeit not as quickly as the global economy has recovered. The growth in emissions over the last five years was initially spurred by Russia's invasion of Ukraine and the short-term coal use and oil-fired generation that ensued. Heavier than expected coal use in China (in part owing to a drought affecting hydropower) saw emissions continue to rise in 2024, but that country's use of coal power is likely to decrease from this year.

In 2024, annual energy-related CO_2 emissions reached 35 Gt. We expect them to slowly decline towards to 34 Gt by 2030, and shrink to 11.3 Gt by 2060 (68% lower than 2024). Coal currently accounts for 44% of energy-related CO_2, oil 31%, and natural gas 25%, with 1% from non-renewable biomass. By 2060, coal emissions decline by 85%, oil by 60%, and gas grows towards 2035 before falling to 39% below current levels.

Sector emissions

In 2024, the power sector emitted 15 Gt (43% of energy-related CO_2), transport 8.8 Gt (25%), and manufacturing 6 Gt (17%), with the remainder coming from buildings, energy sector own use, and other (e.g. agriculture). By 2060, transport becomes the largest emitting sector at 3.7 Gt (33%), followed by manufacturing at 2.7 Gt (24%), buildings 2.1 Gt (18%), and power 1.8 Gt (16%).

Emissions fall to one-third of today's level by 2060

World energy-related CO_2 emissions by fuel source ($GtCO_2$/yr)

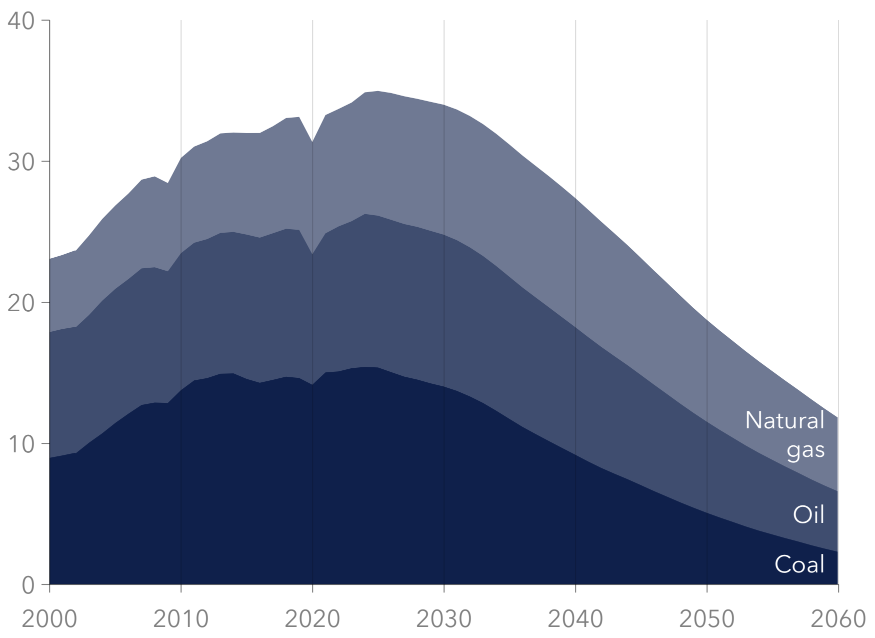


FIGURE 8.1 | Non-renewable bioenergy contributes less than 1% of emissions. By 2050, bio-based CCS increases capture and by 2060 removes 0.5 $GtCO_2$/yr.

Sectors decarbonize at different speeds, power quickest

World energy-related CO_2 emissions by sector ($GtCO_2$/yr)

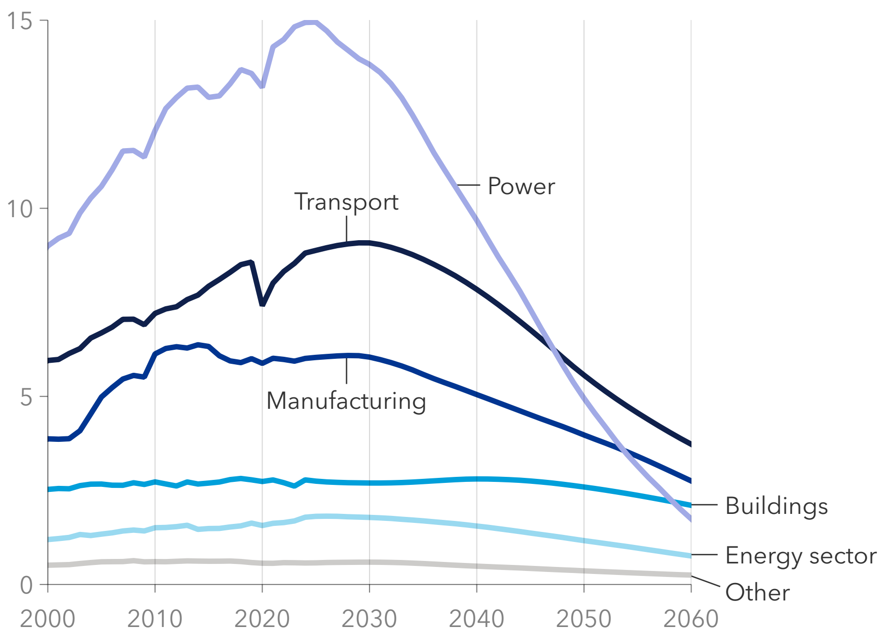


FIGURE 8.2 |

- The **power** sector decarbonizes fastest by 2060 as most new capacity comes from wind and solar, fossil-fuel plants retire, nuclear expands, and some fossil generation adopts carbon capture. Overall, power-sector emissions fall by 88%.
- Significant declines in **transport** emissions will occur as road transport electrifies and low-carbon fuels enter shipping and aviation, delivering a 58% reduction by 2060. Rising EV penetration increases electricity demand, which is progressively decarbonized upstream.
- Emissions from **manufacturing** fall by 55% by 2060 through electrification, fuel switching, efficiency, and CCS. High-temperature processes remain costly and technically challenging to decarbonize, limiting deeper reductions, but an increasing share of high heat based on electricity starts to make a difference towards the end of our forecast period.
- Efficiency gains and heat-pump adoption reduce **buildings** carbon intensity, but growth in population and demand for heating, cooling and hot water combined with a rising demand from AI data centres, increase energy demand leading to emissions only falling 25% to 2060.

Regional emissions

Emission paths diverge across regions. Greater China peaks in 2030 and then declines to 85% of 2024 levels by 2060. Emissions in the Indian Subcontinent rise rapidly to the 2030s, plateau, and then decline from 2040 to end 38% lower than today in 2060. Sub-Saharan Africa's emissions increase 42%. Other regions reduce with Europe reaching net zero, OECD Pacific (92% reduction), and North America (85% reduction) by 2060. On a per-capita basis in 2060, North East Eurasia has the highest emissions at 4.5 tCO_2/yr, followed by the Middle East and North Africa (2.7 tCO_2/yr) and North America (1.9 tCO_2/yr).

Process-related emissions

Beyond fuel combustion, industrial process emissions were 3.4 Gt in 2024, about half from cement calcination and the remainder from ammonia, anode use, coke ovens, lime, and other chemicals. A near-term rise from construction and industrial activity over the next five years gives way to gradual declines in emissions from efficiency gains and carbon capture that result in annual emissions of 3.1 Gt by 2060 (9% lower than today).

Land-use emissions

Land-use emissions from agriculture, forestry, and other land use (AFOLU) are not modelled in our energy outlook, but are included in our estimate of global warming because they exceed 4 $GtCO_2$/yr – almost 10% of total CO_2 emissions. Historically averaging 5 $GtCO_2$/yr with large variability, recent research shows a gradual decline of land-use emissions to reach 3.6 $GtCO_2$ per year in 2023 (Friedlingstein et al., 2024). However, extreme wild-fires in South America increased AFOLU emissions back to 4.2 $GtCO_2$ in 2024 (Hausfather, 2024).

Despite large uncertainties, especially from forest loss and fires (MacCarthy et al., 2025), we still expect AFOLU emissions to decline for three reasons. First, AFOLU abatement is generally low-cost and co-beneficial (e.g. avoided deforestation and methane cuts in reducing crops/livestock). Second, demographic decline, yield gains, and urbanization reduce per-capita land pressure. Third, global climate policy increasingly focuses on land use, including reduced deforestation and results-based finance supported by improved measurement, reporting, and verification from remote sensing. On this basis, we expect AFOLU emissions to decline gradually to 3.5 Gt by 2030, then fall more rapidly to 1.3 Gt by 2060, reaching net zero around 2080 and turning net negative thereafter, removing 1.8 Gt annually by 2100.

Emission paths diverge across regions, but almost all decline towards 2060

Energy-related CO_2 emissions by region ($GtCO_2$/yr)

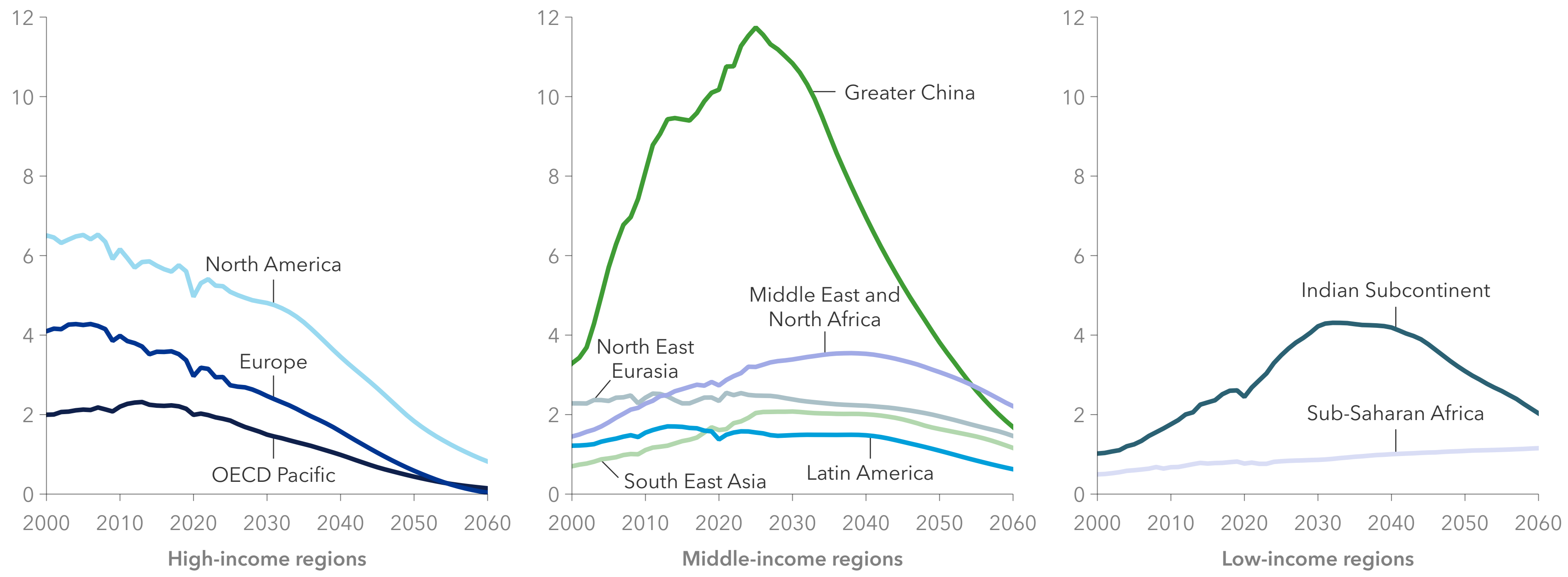


FIGURE 8.3 |

Carbon capture and removal

We see an increasing uptake of CCS technologies to limit atmospheric accumulation of CO_2 from fossil use. CCS captures CO_2 from concentrated sources such as power and industrial facilities, while DAC removes CO_2 from ambient air. Captured or removed CO_2 can be stored geologically or used, but our forecast counts only capture plus storage, as use is expected to be marginal in comparison. By 2060, 2.2 $GtCO_2$ will be captured and stored annually, up from negligible levels in 2024. CCS provides 84% of removals and direct air capture (DAC) contributes about 16% (0.4 Gt) by 2060. Roughly one-quarter of CCS capacity in 2060 is in fossil and bioenergy power plants. Despite this growth, capture and removal together offset less than 10% of energy-related emissions in 2060. The IPCC, *AR6 Synthesis Report* (2023) underscores that the window to meet a sub-2-degree Celsius outcome is narrowing and that CO_2 removal will likely be needed in addition to deep emissions cuts. See Section 4.2 for a detailed description of our CCS forecast.

Methane

Methane (CH_4) is the second-largest driver of anthropogenic warming after CO_2, accounting for roughly 30% of the temperature increase since the Industrial Revolution. Around 60% (350 Mt/yr, 10 $GtCO_2e$/yr) of annual CH_4 emissions are anthropogenic, close to one third of energy-sector emissions; the rest arise from natural sources (e.g. wetlands). It causes a higher global warming effect than CO_2, but it has a shorter atmospheric lifetime (10 years). Because of this, methane has great mitigation potential, especially where captured methane has a monetary value and can be used as fuel.

Methane emissions from fossil fuels reach 128 Mt in 2030, slightly lower than today's level of 140 Mt. Emissions fall further to 100 Mt toward 2040 and reach 50 Mt by 2060, mainly owing to lower coal and oil demand. Today, methane emissions from natural gas are 40% of the total energy emissions, with coal and oil each having approximately 30%. We estimate these shares will change gradually, with coal reducing heavily due to demand reduction. By mid-century, 54% methane emissions from fossil fuels will be due to the extraction, transmission, and distribution of natural gas, with oil contributing 26%, and coal 20%.

Methane has great mitigation potential, especially where captured methane has monetary value as a fuel.

8.2 GLOBAL WARMING FROM COMPOUNDING EMISSIONS

We determine the climate response and associated temperature increase based on our forecast future levels of CO_2 emissions. We focus only on first-order effects and do not include possible major tipping points and feedback loops, such as melting permafrost and peat fires, which would accelerate global warming further. Other climate implications, including those directly associated with emissions (e.g. acidification of the oceans) and indirect consequences (e.g. sea-level rise or precipitation changes), are not dealt with in this Outlook which concentrates on the energy transition and its associated CO_2 emissions.

Carbon dioxide concentration

Pre-industrial atmospheric CO_2 levels were around 280 ppm and emissions related to human activities, particularly burning fossil fuels, have resulted in a significant increase. The most recent measurement in June 2025 recorded a record high of 426.9 ppm (NOAA GML, 2025), continuing the steady rise in atmospheric CO_2 throughout the last 170 years (Figure 8.4).

We project that anthropogenic CO_2 emissions will continue, albeit on a declining trajectory from 2026 onwards. Unlike methane, which remains in the atmosphere for about 10 years (IPCC, 2001) before breaking down into CO_2 and water, atmospheric CO_2 persists for centuries to millennia (Archer et al., 2009). This long lifetime makes cumulative CO_2 concentrations a direct indicator of long-term global warming.

A near-linear causal relationship links cumulative anthropogenic CO_2 and the increase in global mean temperature (IPCC, 2021). Consequently, expected warming can be inferred from the net cumulative amount of CO_2 in the atmosphere. Conversely, to limit warming below a specified threshold with

CO_2 concentration keeps increasing in the atmosphere

Recent global monthly mean CO_2 (ppm)

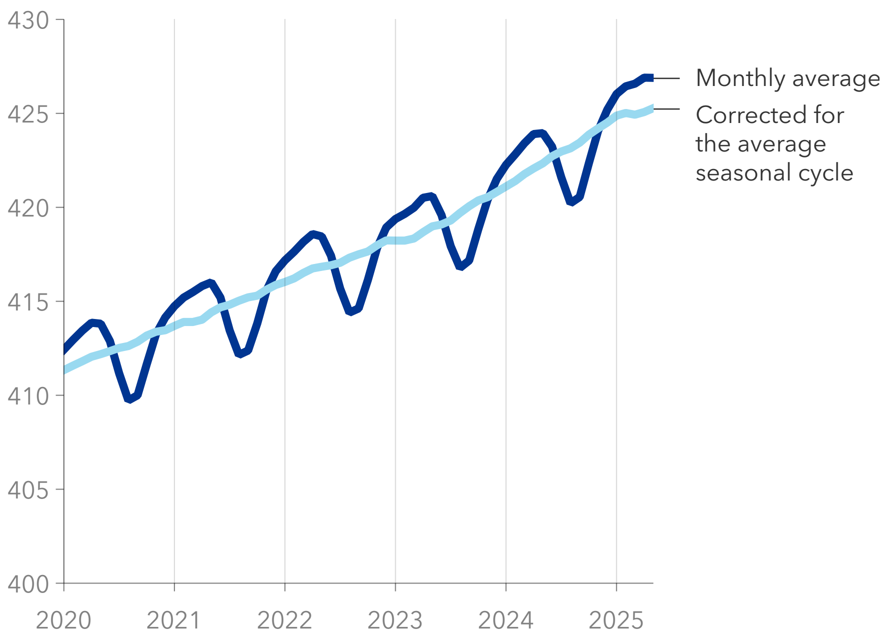


FIGURE 8.4 | Data source: Lan, Tans, Thoning (2025)

a given probability – while accounting for other anthropogenic GHG and aerosols – we can derive the maximum allowable cumulative anthropogenic CO_2 emissions. This is commonly referred to as the 'global carbon budget'. These budgets are conditional on climate sensitivity based on IPCC AR6, which assesses an equilibrium climate sensitivity of 3.0°C (likely 2.5 to 4.0°C) per CO_2 doubling. However, some recent work indicates this could be too low and points to higher sensitivity of between 4 and 5°C per CO_2 doubling (Hansen et al., 2025). If this is correct, remaining budgets are smaller and our forecast energy transition would lead to an even higher temperature.

The current emissions pathway leads to 2.2°C of global warming by 2100

World CO_2 emissions ($GtCO_2$) and associated carbon budgets

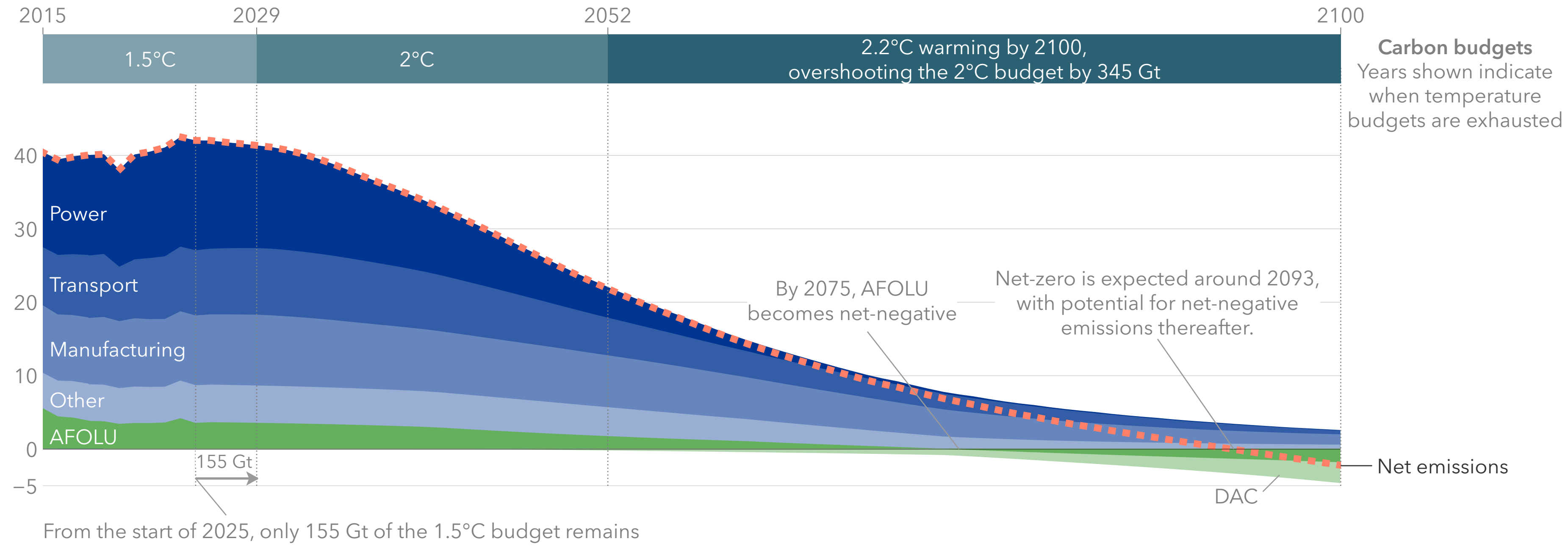


FIGURE 8.5 | DNV Energy Transition Outlook temperature estimates use the IPCC Sixth Assessment Report (AR6) carbon budgets.

The global carbon budget

Carbon budget estimates carry several sources of uncertainty: the accuracy of historical emissions data, the estimate of warming to date, the contribution of non-CO_2 GHGs to current warming, Earth system feedbacks, and the additional warming that may occur after net-zero emissions are reached. These uncertainties become more consequential as temperatures approach policy targets (e.g. exceeding 1.5°C).

Despite these caveats, the carbon-budget framework remains a useful way to map future warming outcomes to alternative emissions pathways. Our temperature estimates adopt the IPCC *Sixth Assessment Report* (AR6) 'likely' budgets (67% probability) (IPCC, 2021). Under AR6, the remaining carbon budget from 2020 is approximately 400 $GtCO_2$ to limit warming to 1.5°C and 1,150 $GtCO_2$ to remain below 2.0°C. These budgets already incorporate non-CO_2 emissions. However, variations in CH_4 (e.g. from fossil fuels and agriculture) and aerosol emissions can materially shift the budget. We align our assessment with IPCC 'very low' and 'low' non-CO_2 pathways, which broadly track our CO_2 trajectory. Higher non-CO_2 emissions would reduce the available CO_2 budget and increase associated warming.

Using these AR6 budgets and our cumulative CO_2 pathway, we estimate that the 1.5°C budget is exhausted in 2029 and the 2.0°C budget is exhausted in 2052.

Our most likely global warming projection

Calculating the temperature at which global warming stabilizes by 2100 assumes that all GHG emissions and other drivers fall to (or below) zero at some point before the end of the century. That point is after 2060, beyond the limit of our detailed forecast. We therefore extend our analysis, with focus on emissions pathway to 2100. Emissions decline steeply by 2060, supported by increasing CCS. The decline in emissions, combined with negative emission technologies and land-use changes, achieves net zero by 2093, with the potential for net-negative emissions thereafter.

We do not assume grand technological breakthroughs in the second half of the century (e.g. low-cost, environmentally benign geo-engineering).

Our emissions forecast limits CCS capture to sectors where it is already plausible to capture emissions, combined with an increasing deployment of negative emission technologies. This yields cumulative emissions of about 210 $GtCO_2$ from 2060 to 2100 (Figure 8.5). Using AR6 climate-response parameters and evaluating our pathway against the 67%-probability 2.0°C budget, the resulting overshoot of 345 $GtCO_2$ implies end-century warming of approximately 2.2°C above pre-industrial levels by 2100.

Using AR6 climate-response parameters and evaluating our pathway against the 67%-probability 2.0°C budget, the resulting overshoot of 345 $GtCO_2$ implies end-century warming of approximately 2.2°C above pre-industrial levels by 2100

Net zero in 2050 is beyond reach

Net-zero anthropogenic CO_2 emissions represent a 'magic' inflection point, effectively halting additional global warming. The reality is a little more nuanced: it involves uncertainties and is dependent on the amount of emissions from other GHGs and aerosols. However, warming is likely to stop once CO_2 emissions reach net zero (Hausfather, 2021). If net-negative emissions follow thereafter, global temperatures will eventually start falling.

Achieving net zero by 2050 is not a magic point in time. The term 'net zero by 2050' grew popular after the *Special Report on Global Warming of 1.5°C*, that found the world needs to reach net zero by around 2050 if it is to limit global warming to 1.5°C and thus avoid the dangerous climate change consequences that the IPCC expects for a temperature increase above that threshold (IPCC, 2018). However, that assessment was based on a trajectory in which emissions began declining after 2018, with a steep reduction continuing toward 2050. Since 2018, global emissions have instead increased, and net-zero CO_2 emissions by 2050 would likely not be sufficient to stay below the 1.5°C threshold.

Our forecast is that by 2050, energy and process-related CO_2 emissions will be at 22 Gt, a reduction of only 43% from today. The gap between our forecast of the 'most likely' energy future to 2050 and net zero by then is huge. Considering current societal priorities, we believe this gap cannot, in any feasible way, be closed through technological advances and/or political will by 2050. Therefore, this year we now state that we find net-zero CO_2 emissions in 2050 beyond reach.

The natural question is then: *when are we likely to reach net-zero emissions?*

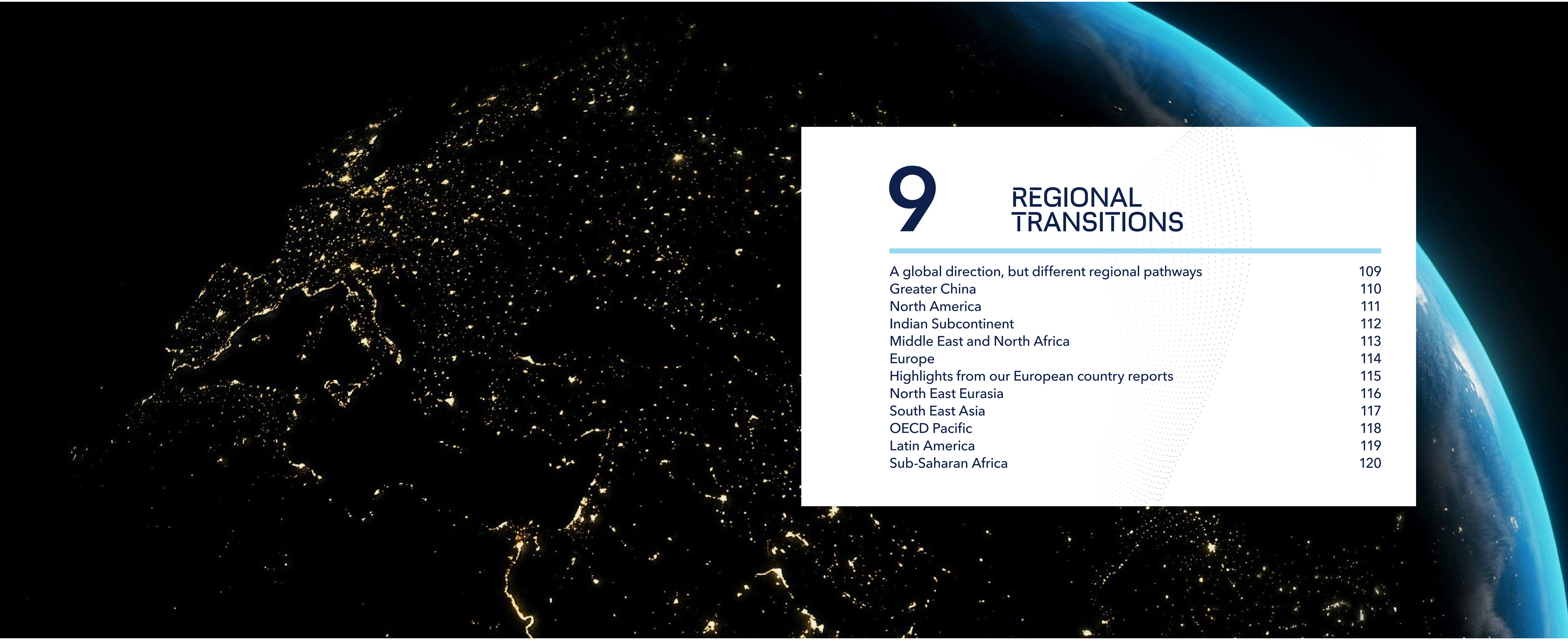
We expect global net-zero CO_2 emissions in the early 2090s. After that, further emissions will shrink and the uptake of negative emissions technology to continue, turning emissions effectively net negative. As a result, the global temperature will stabilize around that time at 2.2°C above pre-industrial temperatures.

In 2023, we published *Pathway to Net Zero*, a 'backcast' that found a plausible scenario for achieving net-zero emissions by 2050. The pathway we found in that report was extremely challenging. It had a significant carbon budget overshoot in which warming would be above 1.5°C for a while and large negative emissions would be needed in the second half of the century to return to 1.5°C of warming.

In the 24 months since that report, we have seen many developments in the wrong direction from the imperative of emission reductions in all sectors and regions. We therefore conclude that the net zero by 2050 scenario we set out is no longer attainable.

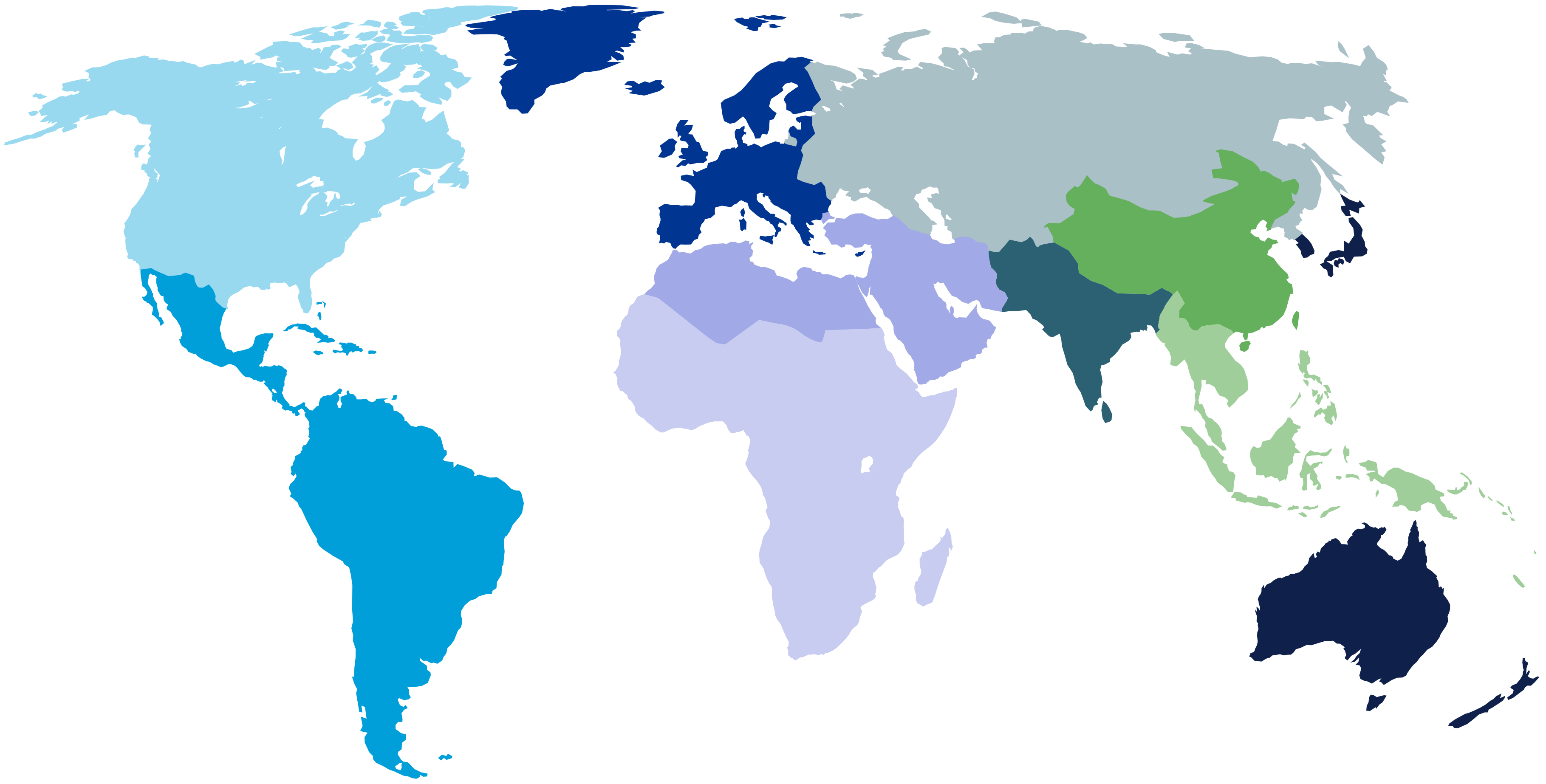
We emphasize, however, that while limiting global warming to 1.5°C by reaching net-zero emissions by 2050 is not feasible, it remains crucial to get as close as possible to the 1.5°C threshold by achieving net-zero CO_2 emissions as soon as possible. With a system as large and consequential as Earth's climate, every tenth of a degree matters.

We find net-zero CO_2 emissions in 2050 beyond reach.



9 REGIONAL TRANSITIONS

A GLOBAL DIRECTION, BUT DIFFERENT REGIONAL PATHWAYS

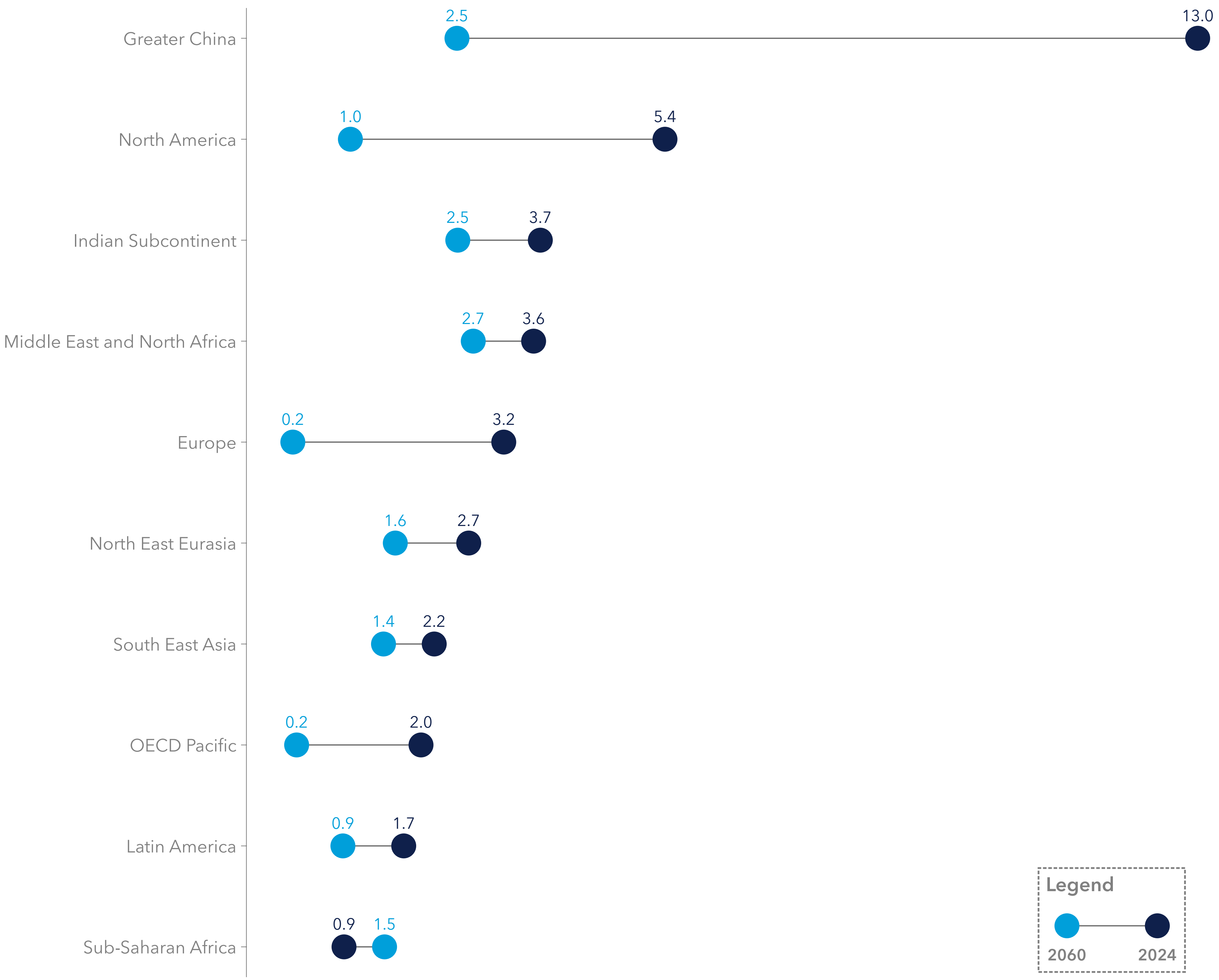


A regional perspective is essential to understanding the global energy transition. Different parts of the world have vastly different starting points, from mature, industrialized economies to rapidly-growing developing nations. This chapter dives into these diverse pathways, offering a more nuanced view of the challenges and progress ahead. Tracking CO_2 emissions provides a critical indicator of how each region's energy system is evolving.

In 2024, the emissions landscape is led by Greater China and North America. Looking to 2060, while most developed regions show a consistent and steep decline, the story is more complex for developing economies. The Indian Subcontinent, South East Asia, and the Middle East and North Africa are projected to see emissions rise and peak between 2030 and 2040 before beginning their decline. Sub-Saharan Africa is the only region where emissions continue to grow through 2060, reflecting a different stage in its economic and energy transition.

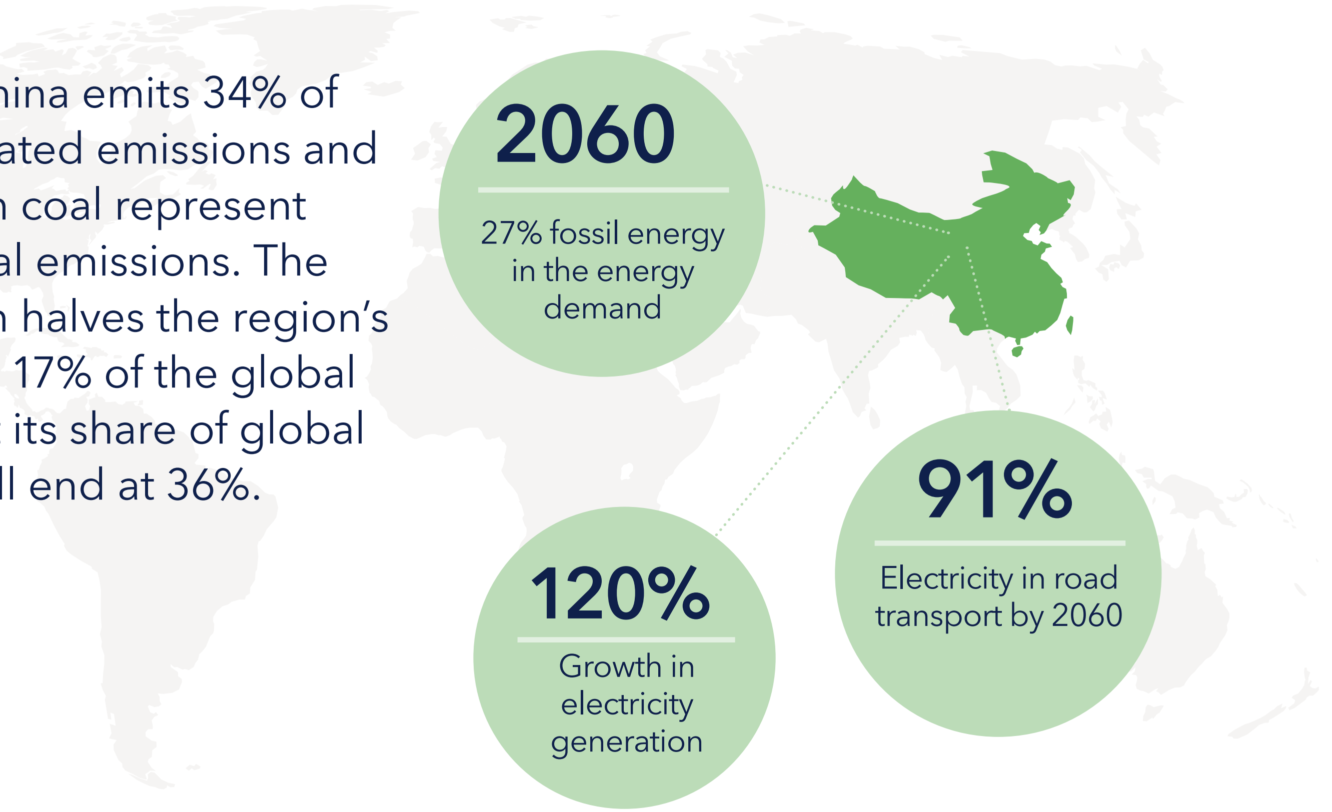
Greater China is by far the world's current largest emitter, but regional differences will be much smaller by 2060

Regional energy- and process-related CO_2emissions ($GtCO_2$/yr)



GREATER CHINA

Today, Greater China emits 34% of global energy-related emissions and its emissions from coal represent 24% of total global emissions. The forecast transition halves the region's emission share to 17% of the global total by 2060, but its share of global coal emissions will end at 36%.



- China is very focused on its energy security, but it will only be in the late 2050s that the region halves its oil and gas imports from present levels. By 2050, fossil energy sources combined will provide only 6% of the electricity but, this share contributes to letting fossil energy sources remain bigger than renewables in the total energy demand. In 2060, electricity generated will be 120% higher than today; 89% of that will come from renewables, 10% nuclear, and just 1% fossil-fired.
- By 2060, the main increases in demand for electricity comes from buildings (77% covered by electricity compared to 40% now) and transport (where electricity will supply 44% of the energy demand).
- China's manufacturing sector is by far the world-leading supplier of equipment for electrification both on the supply (PV, wind) and demand (EV, battery) sides.
- By 2060, China will have net emissions of 2.5 $GtCO_2$, 83% lower than at present, but not meeting the net-zero emissions goal set for that year.

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Coal: spectre at the renewables feast

China is responsible for over a third of global energy-related emissions. The main culprit is coal which accounts for 70% of the region's emissions, with 72% of those emissions produced by coal-fired power stations.

Peak coal is therefore a big deal in China. Our analysis suggests it is happening now. This may seem counter-intuitive because there are net capacity additions of coal power in the next few years. However, we believe this will be outweighed by:

– The continued rapid expansion of cheaper renewables. Solar alone will be 26% of the power mix by 2030 and will go on to deliver more than half of all electricity in 2060. Both nuclear and wind will grow six-fold in this period.

– New regulations on coal power, including efficiency requirements for all coal plants by the end of 2027. China introduced payments to maintain, but not necessarily use, a certain level of capacity as they now consider coal to be a peak load, not base load resource (NDRC, 2024). However, coal is still used for 'grid stability' (NDRC et al., 2025), a role that may conflict with the intended reduction in generation.

We predict a 86% reduction of coal for power by 2050. That will happen without a substantial decrease in the installed capacity, giving an average capacity (utilization) factor of 9% for China's coal plants by then.

By the early 2050s, manufacturing will consume more coal than the power sector. By 2060, manufacturing will consume 7 EJ/yr of energy from coal, more than half of the coal consumption in China in that year. That fraction of coal use is the main contribution to why China will miss its climate goal.

Greater China dominates global coal consumption to 2050
World CO_2 emissions from coal consumption ($GtCO_2$/yr)

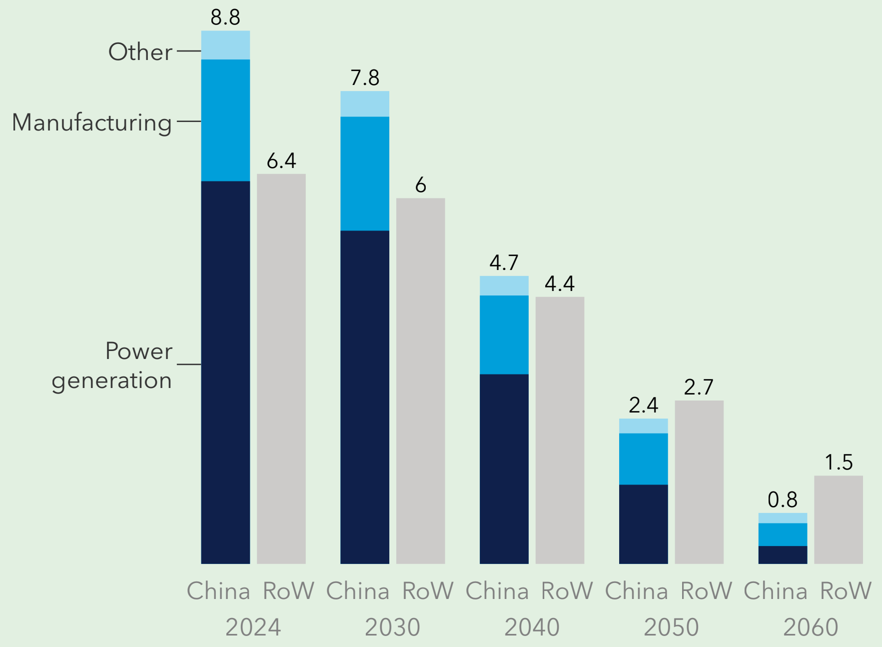
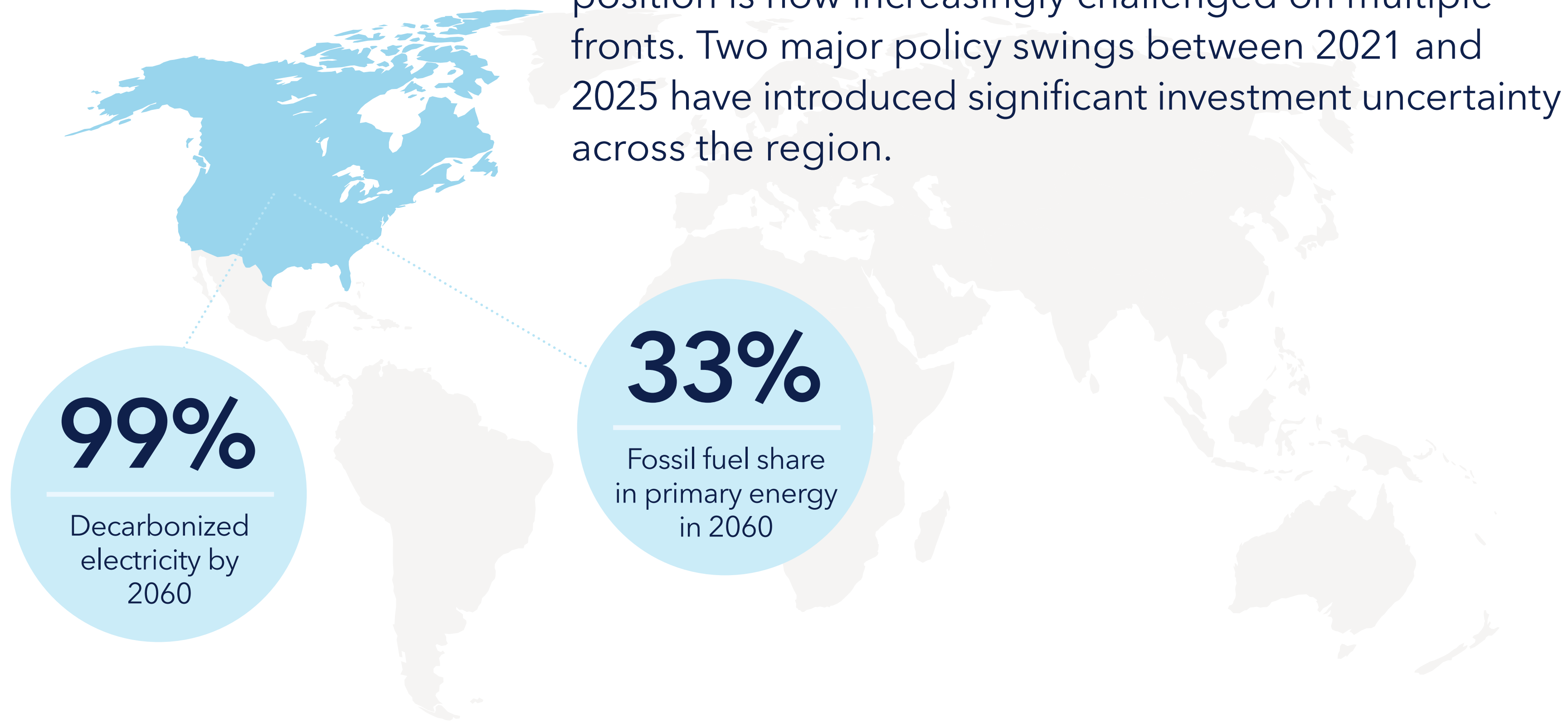


FIGURE 9.1 | RoW: Rest of the World.

NORTH AMERICA

North America is a global energy superpower, but that position is now increasingly challenged on multiple fronts. Two major policy swings between 2021 and 2025 have introduced significant investment uncertainty across the region.



- Electricity demand in the region has been relatively flat over the past two decades. **We now project it to grow, driven initially by AI data centre expansion**. Over the longer term, EVs and grid-connected electrolysers will further increase electricity consumption.
- Despite policy volatility and the rollback of support mechanisms, **solar PV will remain the most cost-competitive option for new capacity additions** in the near term in North America, thanks to its low levelized cost of energy (LCOE).
- Through 2035, **we expect natural gas to continue playing a key role**, with ongoing operation of existing gas and coal plants and the addition of new gas-fired capacity to meet growing demand for power. However, a multi-year backlog in gas turbine manufacturing and soaring costs will limit the extent to which natural gas can meet the demand increase in the short term.

DNV IS LAUNCHING AN UPDATED, DETAILED REPORT ON NORTH AMERICA'S ENERGY TRANSITION ON **6 NOVEMBER, 2025**

Medium-term energy affordability is a concern

Short-term wholesale power prices are likely to rise with the resurgence of gas-fired generation and a delayed shut-down of coal power (until mid-2030s).

Electricity demand is surging in industries, buildings, and AI-driven data centres. Grid infrastructure is not keeping up and, absent major investment, will drive retail electricity prices even higher.

In the medium term, rising electricity costs are problematic for low-income households, smaller businesses with little buffer for rising costs, and energy-intensive businesses. Hyperscalers paying higher prices for their electricity needs risks increasing power prices for all other customers.

The transition is likely to revert to decarbonization and low-cost renewable energy. We forecast that from mid-2030s, wind and solar will begin displacing gas. By 2045 to 2060, renewables dominate the mix, offering long-term price stability thanks to zero fuel costs and low operating expenses.

Electricity and gas prices will increase; coal- and gas-fired electricity production increases to 2035, delaying decarbonization

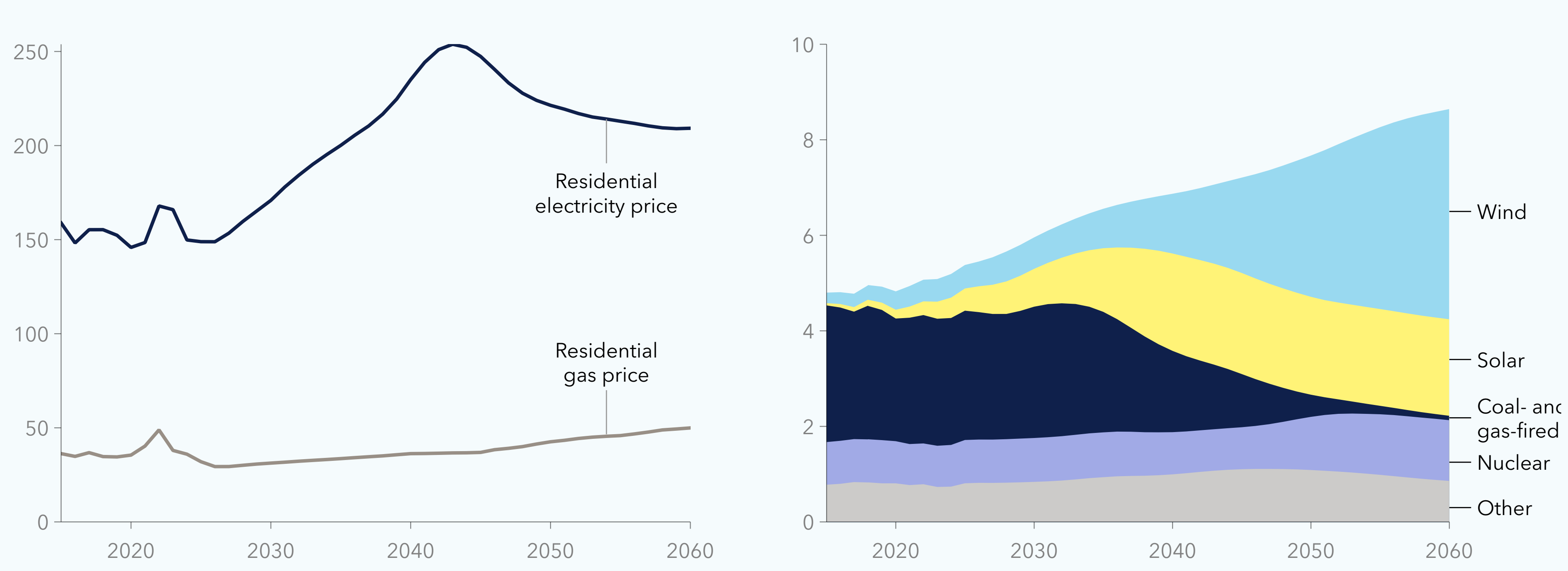
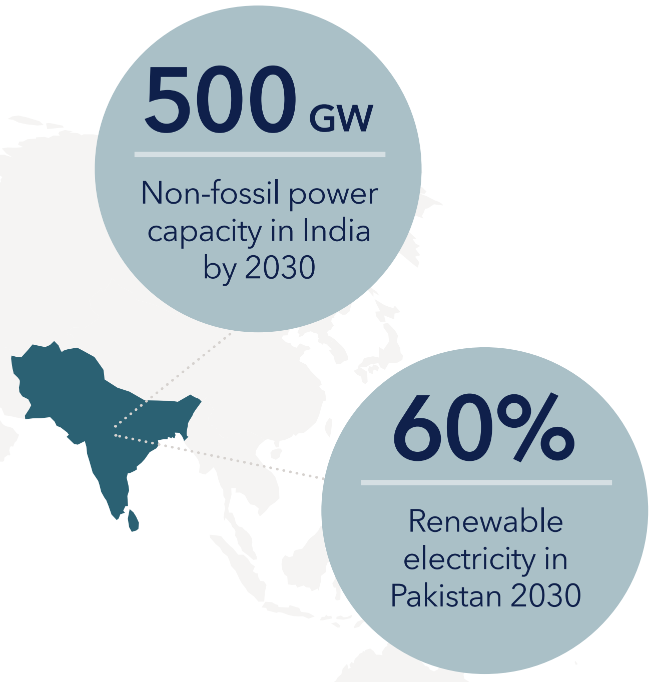


FIGURE 9.2 | Other includes oil-fired, geothermal, bioenergy, and hydropower.
Historical data source: IEA WEB (2025)

INDIAN SUBCONTINENT

The most populous of the 10 regions: 1.9 billion people today, rising to 2.4 billion by 2060. With GDP per capita tripling as well, one could expect runaway regional energy demand, but in fact it rises moderately by 74% to 73 EJ/yr, owing to the rising proportion of efficient, renewable-based power in the energy mix.



- **Development through transition:** Economic development and energy security are dominant themes across the subcontinent. Electrification is key to both the energy transition and economic development; it will meet 41% of final energy demand by 2060, compared with 18% today. However, electricity punches above its weight – providing 56% of the useful energy.[1]

- **Targets:** India, Pakistan, and Bangladesh want 30% of new car registrations to be EVs by 2030. Pakistan has set a target of 60% renewables and India 50% for non-fossil electricity capacity by 2030. Bangladesh targets 20% and 30% electricity generation from renewables by 2030 and 2040, respectively.

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- **Peak emissions in late 2030s:** Coal is currently the primary energy source in both power and manufacturing. As these sectors decarbonize, we forecast regional emissions will peak the 2030s at 4.8 $GtCO_2$/yr, before gradually decreasing through to 2060.

- **Homegrown renewable tech:** The PV panels and wind turbines needed to generate the forecast renewable energy are mostly imported from China. However, as part of its transition story, the region is incentivizing domestic renewable manufacturing with the government funding national missions to deliver on technology development goals.

[1] 'Useful energy' is the energy that has been utilized for a specific purpose like work, heat, or light after accounting for conversion losses. 'Final energy' refers to energy directly delivered to users such as petrol, gas, or electricity before losses are incurred in end use.

Long-term energy independence through renewables

India makes up 80% of the subcontinent's economy, strongly influencing the region's overall energy transition trend. *Viksit Bharat @2047* is India's goal of becoming a developed nation by its centenary of independence.

India achieved installing 50% of non-fossil electricity capacity in 2025, 5 years ahead of the 2030 target. By 2047, the country targets 1,800 GW of renewable electricity generation capacity (Ministry of New and Renewable Energy, 2025). Bangladesh and Pakistan are pursuing their renewable goals of 20% and 60% respectively by 2030. India is expanding its pumped hydro and battery storage for 'round-the-clock' availability of renewable power in its grid.

We forecast the region to achieve 525 GW in renewable capacity installations by 2030 through a combination of utility solar PV, rooftop solar, and wind, including nearly 70 GW of solar+storage.

We predict demand for oil and coal will peak in the 2040s, but imported natural gas remains a key fuel through mid-century for buildings and manufacturing. Coal-fired electricity will peak in the 2030s, but direct use will remain significant in manufacturing. While oil in transport will peak in the 2040s, it will be the largest energy carrier for the sector through mid-century.

Electrification is the main engine of decarbonization and energy independence. We expect power consumption to increase from 7.3 EJ/yr to 25 EJ/yr, led by transportation and manufacturing, with projected growth in electricity demand of 90% and 70%, respectively. Overall, electricity will be 80% renewable by 2050 and 88% by 2060. Moreover, growth in per capita income will outpace expected increases in household energy expenditure. Households will use more appliances while benefiting from the considerable energy efficiencies associated with electrification.

Transition through non-fossil generation capacity growth

Share of electricity generation by power station type

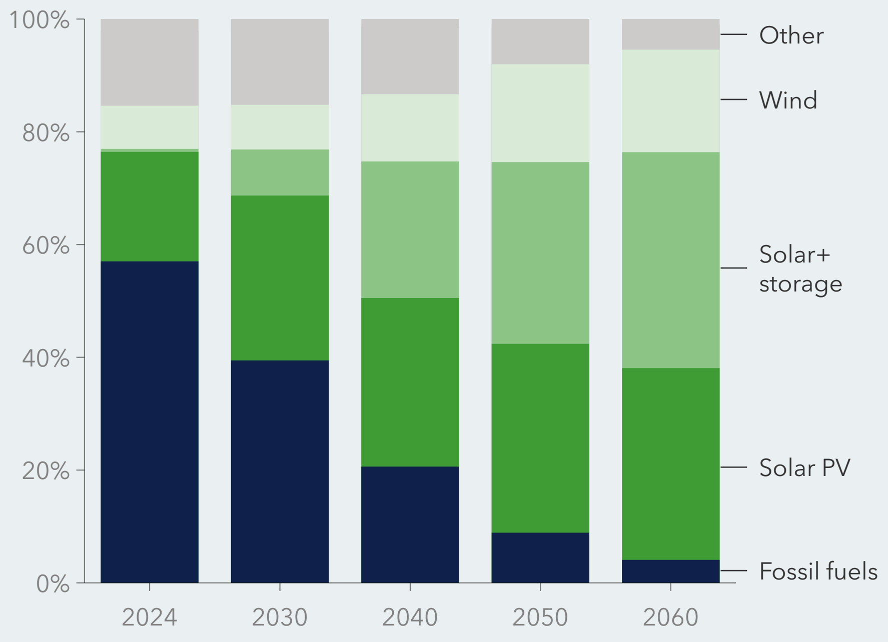
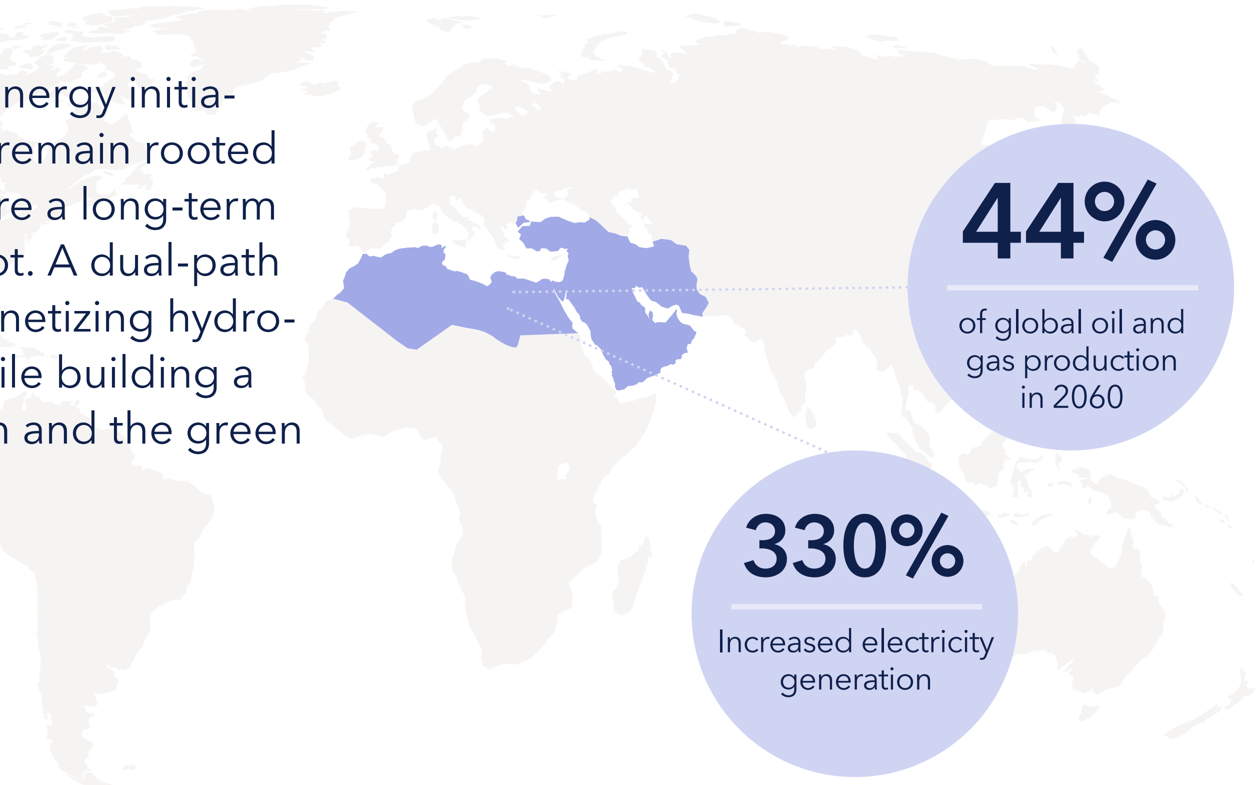


FIGURE 9.3 | Other includes bioenergy, geothermal, hydropower, and nuclear. Fossil fuels include oil-, gas-, and coal-fired.

MIDDLE EAST AND NORTH AFRICA

Despite bold clean energy initiatives, the region will remain rooted in fossil growth before a long-term decarbonization pivot. A dual-path strategy involves monetizing hydrocarbon strengths while building a foothold in hydrogen and the green economy.



- The region targets increased **market dominance in oil and gas supply**, particularly to Asia, with oil production projected to reach 40 Mbpd by 2030, and a 53% global share by 2060 (22 Mbpd). Current yearly natural gas production of 1,250 Bcm is set to reach 1,660 Bcm by 2040, maintaining 40% of global production by 2060.
- **CCUS** is rapidly expanding to lower hydrocarbon emission intensity and enhance competitiveness while developing **low-carbon hydrogen and ammonia** as new export pillars.
- **Renewable energy** investment is growing quickly. Electricity's share in the energy mix will double by 2060, with renewables providing 87% of power generation by then.
- **Geographic and economic diversity** – ranging from major exporters to net importers – shapes varied energy transition paths in this region. Abundant solar and wind resources could drive significant growth in renewable electricity generation, which we project to reach 6.7 PWh by 2060 depending on country priorities and investment.

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Dominant in oil and gas, strategic diversification

The region remains the largest oil-producing region and is set to overtake North America by 2030 as the largest gas producer as well.

Significant regional investment is accelerating CCUS projects to enhance competitiveness by lowering the carbon intensity of hydrocarbon production while becoming a hub for low-carbon hydrogen and ammonia. Ammonia and methanol projects are on track thanks to leveraging existing gas infrastructure, easier transport, and clear export demand.

Hydrogen and ammonia production are set to reach 6 Mt/yr and 4 Mt/yr by 2040, rising to 25 Mt/yr and 13 Mt/yr by 2060, with primary exports to Europe, followed by Japan and South Korea.

Between now and 2060, population and GDP per capita in the region will grow by 39% and 74% respectively, while primary energy per capita peaks at 107 GJ in 2040, then levels off. This is mainly related to a doubling of electricity's share in energy carriers (from 17% to 34%) in this period. Currently, 87% of power generation comes from fossil fuels, but with renewables surpassing fossil fuels in the power mix by 2040, their share drops to 8% by 2060.

Strategic export diversification

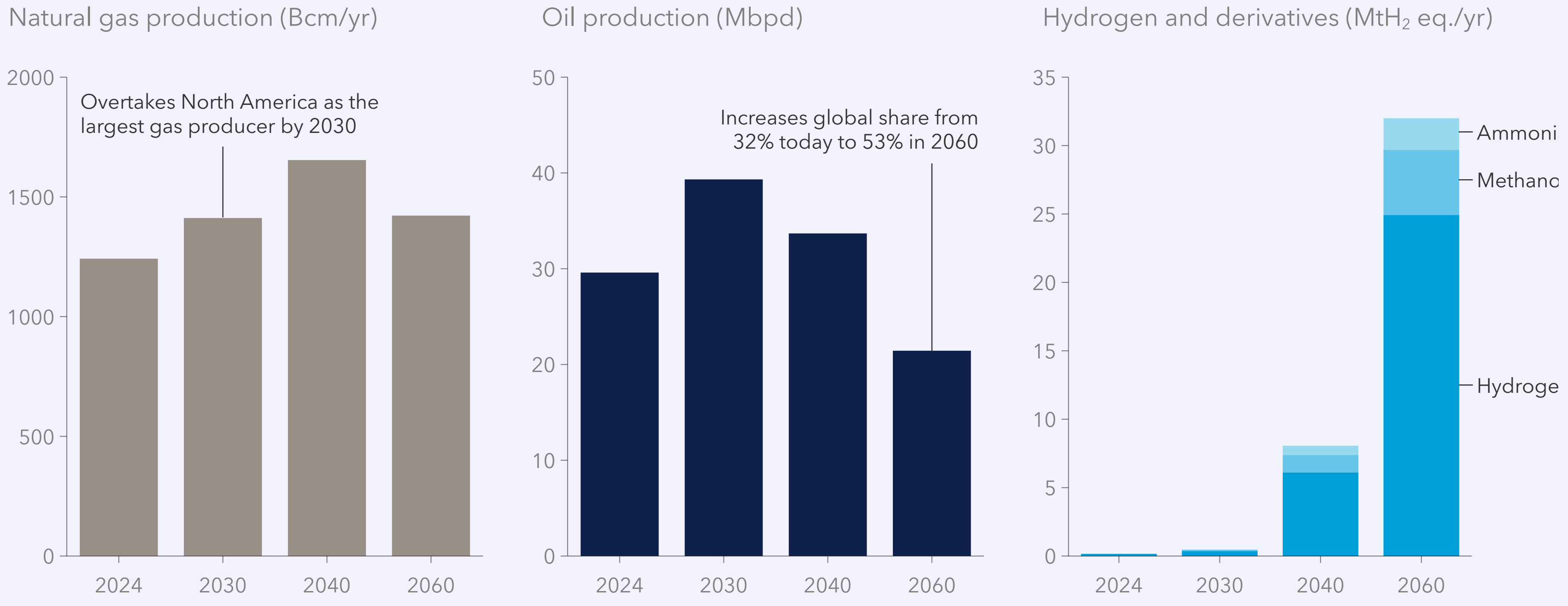
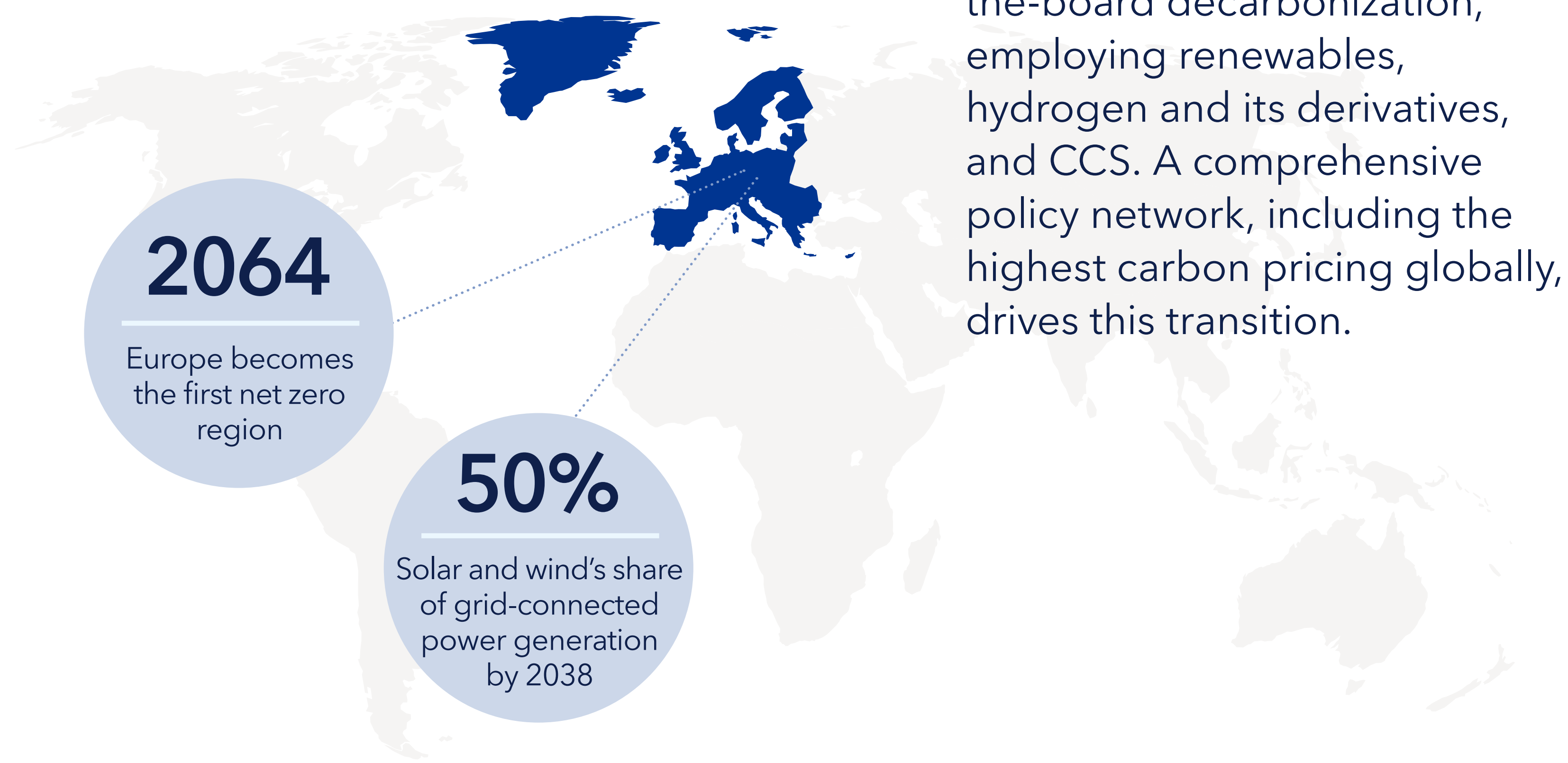


FIGURE 9.4 | 1 tonne of hydrogen equivalent corresponds to around 8 tonnes of methanol and 5.6 tonnes of ammonia.

EUROPE



Europe will lead with across-the-board decarbonization, employing renewables, hydrogen and its derivatives, and CCS. A comprehensive policy network, including the highest carbon pricing globally, drives this transition.

- **Population decline** sets in from 2027. By leading the way on electrification, and hence efficiency gains, final energy demand is set to start declining 0.7% per year after 2030.
- **Electricity demand will grow 110 TWh/yr each year** – the current demand of the Netherlands – after having been stable for 20 years, mainly to power EVs, data centres, and electrolysers. A matched grid buildout is needed, but is currently lagging.
- **Sharpening focus on energy security** will see energy import dependence falling from 56% today to 30% by 2060. NATO military budgets are also rising – partly directed at critical infrastructure – along with a push to reduce reliance on Chinese technology.
- **Europe leads the way in use of hydrogen and its derivatives** in hard-to-decarbonize sectors (5% of final energy demand in 2045 and 9% in 2060).

READ THE FULL REGIONAL OUTLOOK HERE

Households: The last frontier of European decarbonization

Households are Europe's most complex decarbonization challenge. Power generation and manufacturing are already on clear paths to decarbonize, driven by regulation and investment cycles. By contrast, households are fragmented, diverse, and constrained by affordability.

Europe's high energy prices – and wide spark spread between electricity and gas – amplify both the risks and rewards of transition. The shift to heat pumps, solar, batteries, and EVs needs significant upfront spending by households. However, an electric household's monthly saving typically brings its total energy spend below the fossil case over time (Figure 9.5).

These savings are not immediately open to all. Lower-income households, renters, and those in multi-unit buildings face higher barriers. While capital costs for low-carbon technologies fall later, delaying adoption risks locking homes into fossil systems for another full equipment cycle. Closing this gap requires the sustained political will to enact targeted subsidies, financing, and tariff reform. One need to question fiscal policies and market designs that do not make the benefit of low-cost renewable power available to households.

Renewables promise lower overall cost for households but with higher upfront expense

Average energy-related expenditures of two European households (USD/month)

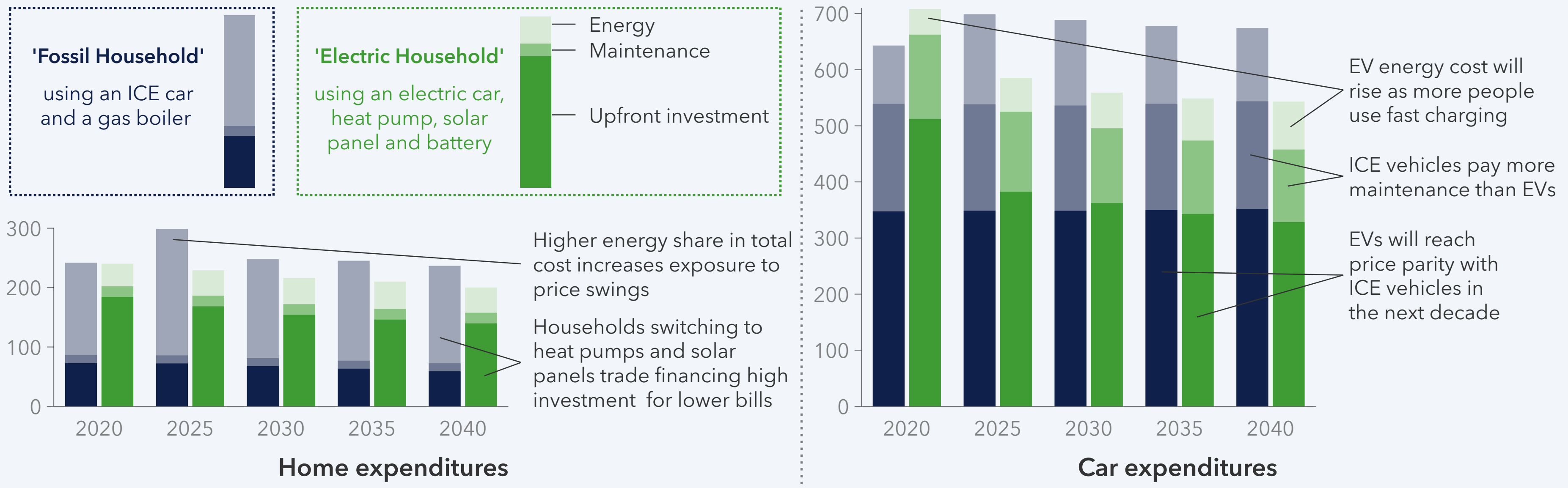


FIGURE 9.5 | Includes capital, operating, and energy costs for heating equipment, cooking appliances, rooftop solar, home battery, and one car per household. Appliance and cooling energy use is included, but not their capital cost. Solar PV capacity is dynamic, averaging 5–6 kW; battery size is 5 kWh per household. Lifetimes: heating 15 years, solar and battery 20 years; cars replaced every 8 years. Technology costs follow modelled learning curves. Energy prices are 245–271 USD/MWh for grid electricity, 66–93 USD/MWh for natural gas, and 1.29–2.12 USD/litre for petrol. All costs in 2024 USD.

HIGHLIGHTS FROM DNV's EUROPEAN COUNTRY REPORTS

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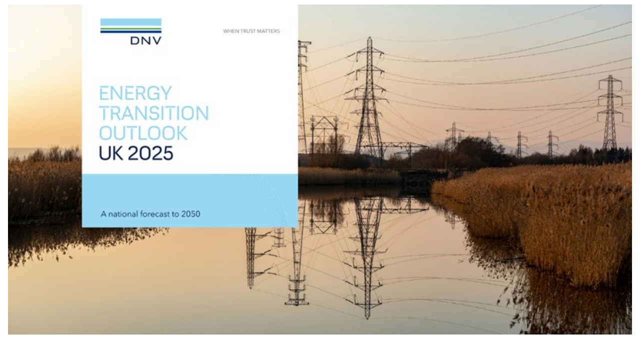
The UK

- The UK is not on track to reach its national emissions targets. By 2030, emissions will drop 55% relative to 1990 levels, not 68%. By 2050, emissions will drop 85%, not 100%.
- The decarbonization of the UK economy is affordable and will reduce average household energy expenditure nearly 40% by 2050 relative to 2021 levels.
- The UK's primary energy supply will shift from fossil fuels to low-carbon sources, with the latter rising from 20% of primary energy today to 65% by 2050.
- Final energy demand will fall by a quarter by 2050 largely due to system efficiency gains from increased electrification.
- Demand for electricity will grow 130% by 2050, with renewable energy sources supplying three-quarters of power generation by 2050.



Norway

- Norway is not on track to reach its national emissions targets. By 2030, emissions will drop 27% relative to 1990 levels, not 55%. By 2050, emissions will drop 75%, not 90-95%.
- Demand for electricity grows 60% from today to 2040. More than a third of this is for hydrogen production.
- Wind is the only scalable option for new power generation. However, local opposition delays onshore wind and high upfront costs delay offshore wind. This results in an unwelcome power deficit in the early 2030s.
- Norwegian energy exports remain central to Europe's energy security and green transition. 30% of Europe's natural gas comes from Norway and this share will grow as Europe's demand for gas declines.

Germany

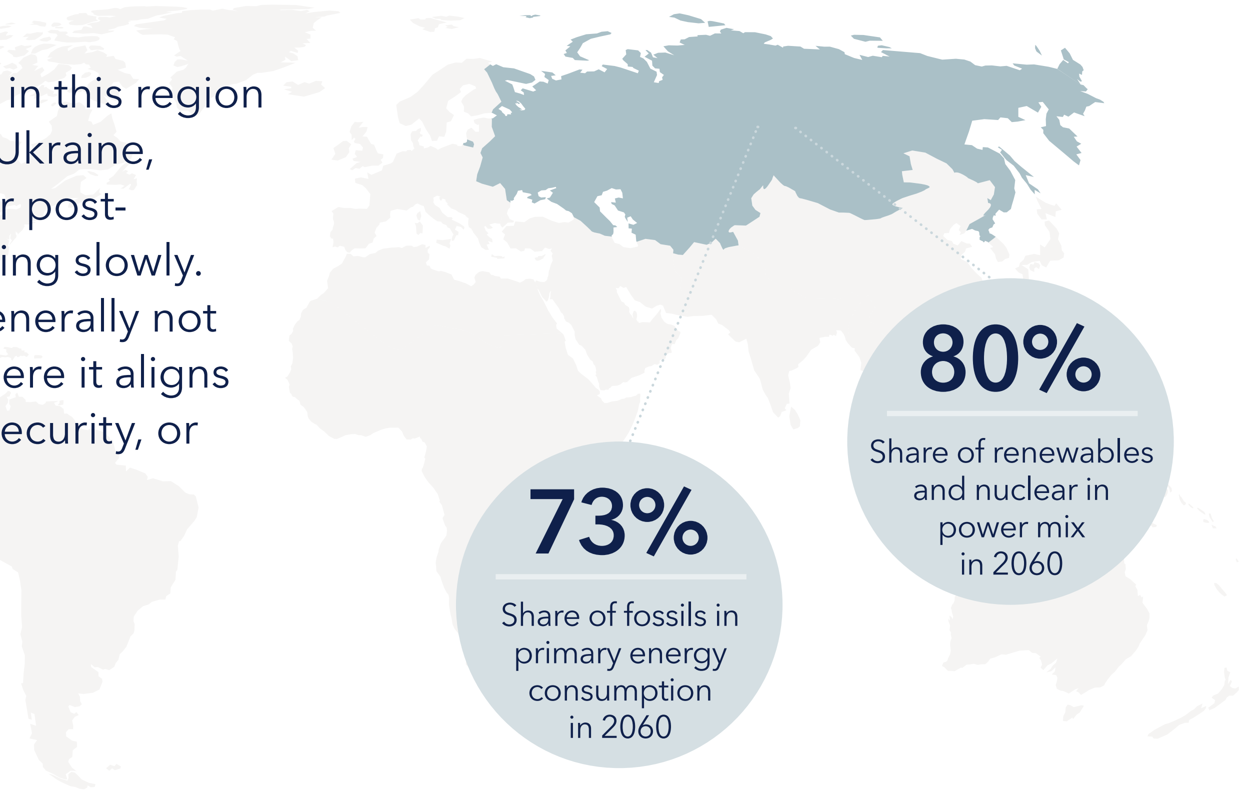
- Germany is not on track to reach its national emissions targets. By 2045, emissions will drop 89% relative to 1990 levels, not 100%.
- Germany will electrify 46% of energy demand by 2050, up from 19% today. Electricity production will be 98% non-fossil by the same year, reducing the need for energy imports from 70% today to 27%.
- Natural gas and hydrogen will co-exist by 2050, with similar demand levels, and one third of hydrogen will be produced domestically.
- Germany will invest EUR 3.3trn in energy infrastructure over the next 25 years.
- Energy prices from an increasingly renewables-dominated system will not disadvantage German industry, but, as elsewhere, fossil fuel-heavy industries will need to adapt their production processes to decarbonize.

Spain

- Spain is not on track to reach its national emissions targets. By 2030, emissions drop 13% relative to 1990 levels, not 32%. By 2050, emissions drop 74%, not 100%.
- Installed renewables capacity in Spain will quadruple by 2050. This surge helps electrify demand and grow electro-intensive industries such as data centres and green hydrogen production.
- Electricity is set to dominate Spain's energy system, but infrastructure bottlenecks and challenges to grid buildout and resilience persist in the short term. Electricity's share in energy demand will grow to 26% by 2030 and 50% by 2050.
- Hydrogen use for energy will begin in the 2030s, mainly for industrial heat. We expect exports to Europe to begin in the late 2040s, reaching around 1.7 Mt/yr by mid-century.

NORTH EAST EURASIA

The energy transition in this region – comprising Russia, Ukraine, Kazakhstan, and other post-Soviet states – is moving slowly. Decarbonization is generally not prioritized, except where it aligns with reconstruction, security, or economic objectives.



- Electricity production is set to rise by 68% by 2060, mainly driven by renewables, though gas will still supply a fifth of power. Low domestic gas prices – depressed by reduced export options due to the Ukraine war – are making coal less competitive and cutting its share by half to 8% by the early 2040s.
- Energy consumption in the region remains mostly flat and heavily skewed toward heating and industry (67% of total energy demand), particularly energy-intensive sectors like metal smelting. There is minimal uptake of electrification technologies like EVs, and thus no structural shift from a consumer-led transition.
- Low carbon prices (e.g. a projected USD 16/ tCO_2 by 2060) mean we expect energy-related CO_2 emissions to decrease by only 40% by 2060 compared with current levels. We forecast this industrialized region will achieve the smallest reduction in emissions.

READ THE FULL REGIONAL OUTLOOK HERE

Pragmatic decarbonization and a slow transition

Although some signs of energy transition are emerging, the region remains largely focused on sustaining its legacy fossil-dominated energy systems. Decarbonization tends to support broader strategic goals – geopolitical positioning, economic resilience, or infrastructure renewal – rather than serve as a core objective. In Ukraine, for example, the destruction of energy infrastructure caused by war presents an opportunity for modernization that may also support decarbonization. International aid and EU-oriented reforms are fostering some alignment with climate goals, yet reconstruction remains the immediate priority.

Russia is exposed to a different set of constraints and drivers. Continuing sanctions and declining fossil fuel exports to Europe have left the domestic market with cheap energy and reduced incentives to pivot away from carbon-intensive sources. At the same time, oil and gas revenues remain strategically important for their central role in funding the ongoing war.

As a result, we expect fossil fuels to still account for nearly three-quarters of the region's primary energy consumption by 2060, with cheap and abundant natural gas making up the vast majority. Although the overall contribution of non-fossil energy sources will remain limited, a stronger focus on renewables in countries like Ukraine and Kazakhstan will push their share in the power generation mix to nearly 80% by 2060.

We expect nuclear energy to comprise 11% of power generation in 2060. However, its expansion is largely motivated by geopolitical and commercial ambitions. Russia is advancing new nuclear business models, such as floating reactors for low-income countries and waste-fuelled next-generation designs that may cut nuclear waste by up to 90% (WNN, 2023). Both Russia and Kazakhstan continue to influence this sector through their domination of the global uranium market.

Non-fossil sources will dominate the power mix by 2060

Share of electricity generation by power station type

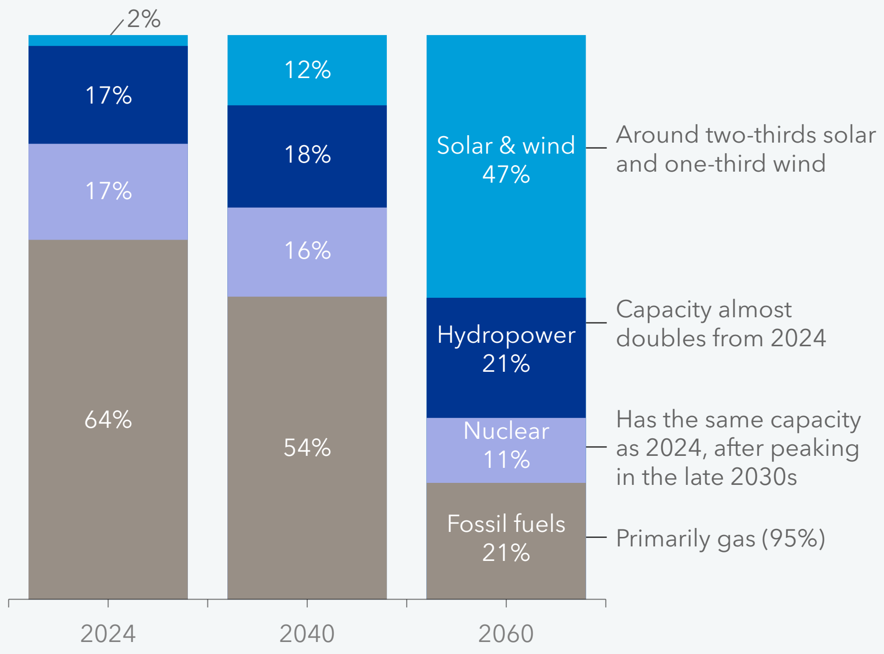
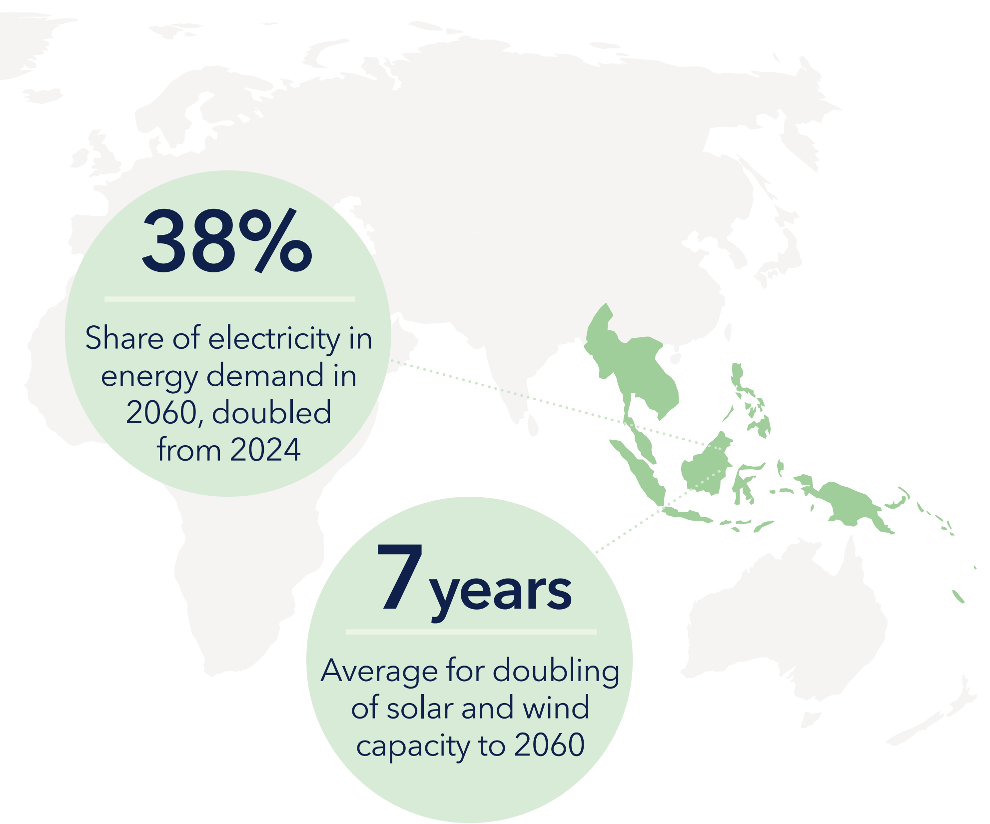


FIGURE 9.6 | Bioenergy and geothermal together account for less than 1% of the total and are thus not shown. Fossil fuels include oil-, gas-, and coal-fired.

SOUTH EAST ASIA

South East Asia is a diverse, resource-rich region where fossil fuels remain dominant. However, renewables are gaining significant momentum through policy reforms and investment as climate change increasingly becomes an urgent issue for the region.



- **Renewable uptake is hampered by dependence on fossil fuels**, which are still considered an important part of economic growth and energy security in the region. Ongoing subsidies exacerbate the entrenchment of fossil fuels by encouraging consumption, but removing them remains politically challenging.
- **Electricity demand is surging**, driven primarily by urbanization, rising incomes, industrial growth, and expanding data centres and fintech sectors in Singapore, Malaysia, and the Philippines. Buildings are the main demand sector, where air conditioning alone accounts for 30% of electricity growth from 2024 to 2060.
- **Regional cooperation is vital** for progressing the energy transition. The ASEAN Power Grid (APG) is the leading collaboration initiative. It aims to support economic development and energy security through shared renewable energy resources. Solar is the main resource that APG will link; we expect capacity to grow from 40 GW today to 100 GW by 2030, and nearly 300 GW by 2040.

READ THE FULL REGIONAL OUTLOOK HERE

Making, but not going, green

South East Asia is emerging as a key player in the renewable energy technology manufacturing landscape. Industrial development is driven by the dual ambitions of economic growth and job creation. The region looks to build upon its position as a viable alternative to the traditional renewable technology manufacturing hub of China as global stakeholders look to diversify supply chains amidst growing geopolitical tensions and uncertain trade dynamics like US tariffs.

Expansion of renewable energy technology capabilities are mostly focused on solar PV, which is established and expanding in Vietnam, Thailand, and Malaysia. EV production is advancing in Thailand, whilst Indonesia is starting to leverage its vast natural resources to ramp up production of EV components and batteries. Indonesia and the Philippines are together the top producers of nickel – around 65% of global mined production (IEA, 2024) – which is a key mineral used in EV batteries and energy storage. However, Chinese companies control around 75% of Indonesia's processing capacity, highlighting possible strategic vulnerabilities.

GDP and emissions growth divergence lags other regions

Indexed to 2000 GDP and emissions (Index: 2000 = 1)

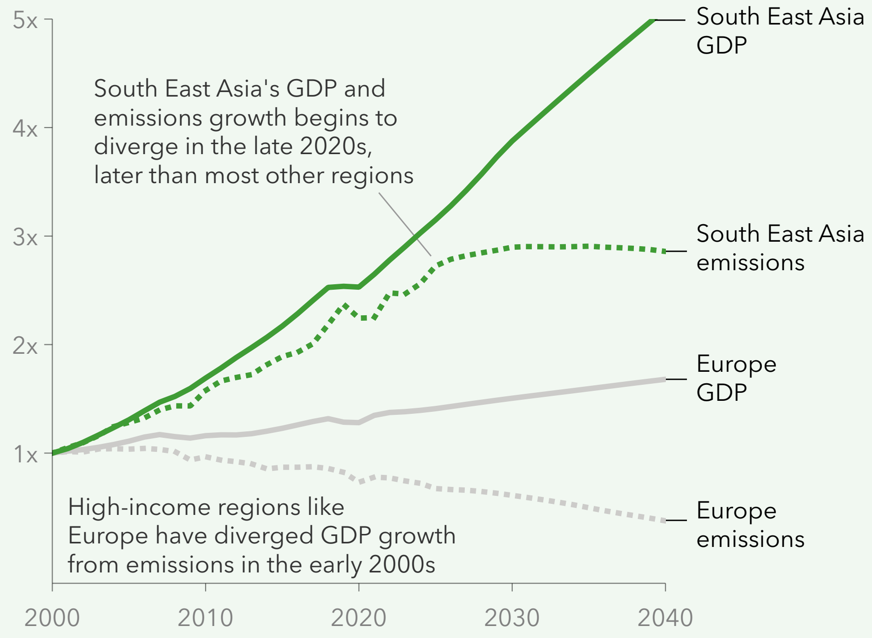


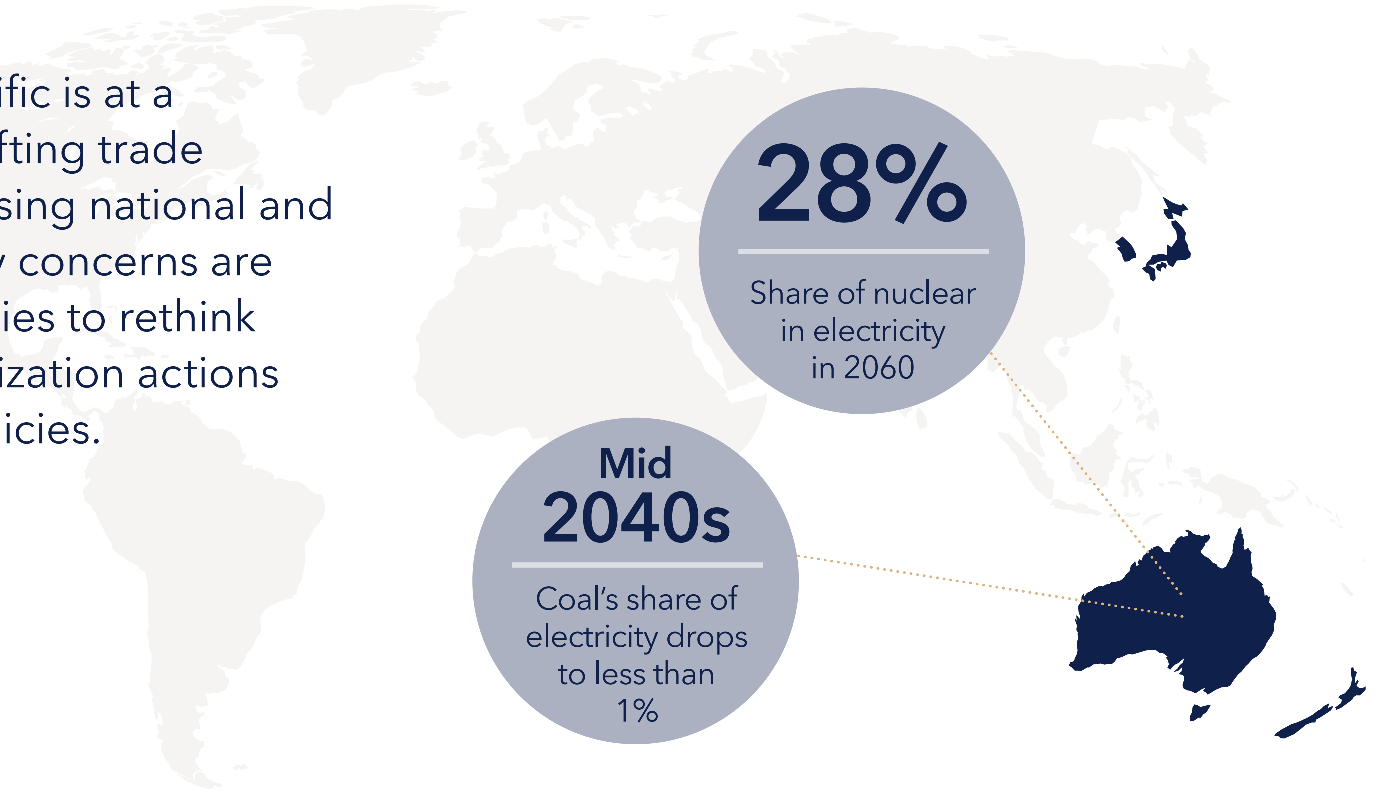
FIGURE 9.7 | South East Asia's growth divergence occurs later than all regions except the Middle East & North Africa when using 2000 as the index year.

Although focused on the international supply chain, increased manufacturing has many benefits at home for South East Asia. Renewable technology manufacturing supports domestic renewable uptake targets and ongoing job creation, with an estimated 3.9 to 5.5 million direct jobs in the renewable sector by 2050 (Bilqis, 2023).

South East Asia is increasingly tapping into global funds to finance its decarbonization efforts. However, the region must look to reduce its reliance on coal and the emissions intensity of its manufacturing sector to continue attracting investment to advance the energy transition. GDP growth diverges from emissions later than in most other regions, highlighting the need for stronger decarbonization efforts. South East Asia's role as a renewable energy production hub will be shaped by its ability to navigate the complex global economic and geopolitical landscape.

OECD PACIFIC

The OECD Pacific is at a crossroads: shifting trade alliances and rising national and energy security concerns are pushing countries to rethink their decarbonization actions and energy policies.



- **Population is declining faster than any other region**, primarily in Japan and South Korea. Population decline, alongside ongoing electrification and efficiency gains, contributes to decreasing energy demand. This is most notable in transport, where demand is more than halved from now to 2060.
- **Grid flexibility** tops agendas as renewables surge. Grid modernization and battery energy storage systems (BESS) are advancing rapidly; Australia leads with over 10 GWh in the pipeline. Japan's solar curtailment subsidies drive BESS uptake, and South Korea has established a central contract market framework for standalone BESS.
- **Hydrogen is shifting from ambitious intra-regional trade to domestic realism.** Australia is moving focus from export to domestic decarbonization in green iron, steel, and ammonia after several major project delays and cancellations due to cost, water access, and permitting challenges. Policy support for hydrogen continues in South Korea, and Japan is piloting hydrogen-ammonia co-firing projects in power and industry.

READ THE FULL REGIONAL OUTLOOK HERE

Securing a resilient energy future

Geopolitical tensions and energy security concerns are reshaping energy strategies across the OECD Pacific region. Japan and South Korea, countries reliant on energy imports, are sensitive to global supply chain disruptions and are therefore accelerating their renewable uptake, as well as reconsidering nuclear power and LNG as transitional fuels. Nuclear additions will come from both new plants and the revival of existing plants which have been temporarily closed. From the late 2020s, the OECD Pacific will have over 20% of electricity sourced from nuclear, the highest share globally. However, nuclear remains politically unviable in Australia and New Zealand.

Tariff discussions and spillovers from US-China tensions are increasing uncertainty in global solar supply chains and raising costs in Japan and South Korea, prompting them to diversify their supply chains and invest in production hubs in South East Asia. Australia and New Zealand are grappling with rising cleantech import costs.

Offshore wind is gaining momentum across the region. Japan and South Korea are expanding auctions and targeting multi-gigawatt scale projects. Australia is expanding its wind pipeline, despite ongoing issues with societal pushback to wind projects and hurdles in permitting processes.

Nuclear is significant for electricity in the OECD Pacific, growing steadily to 2060 alongside quick solar and wind growth

Grid-connected electricity generation by power station type (PWh/yr)

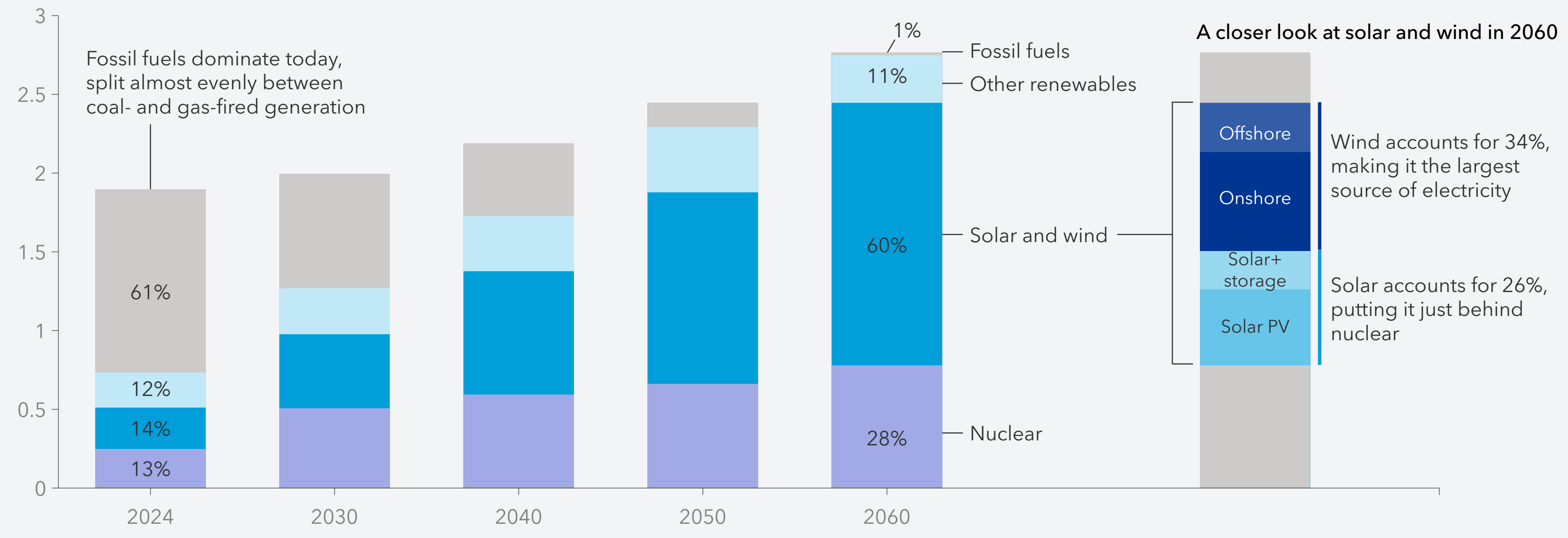
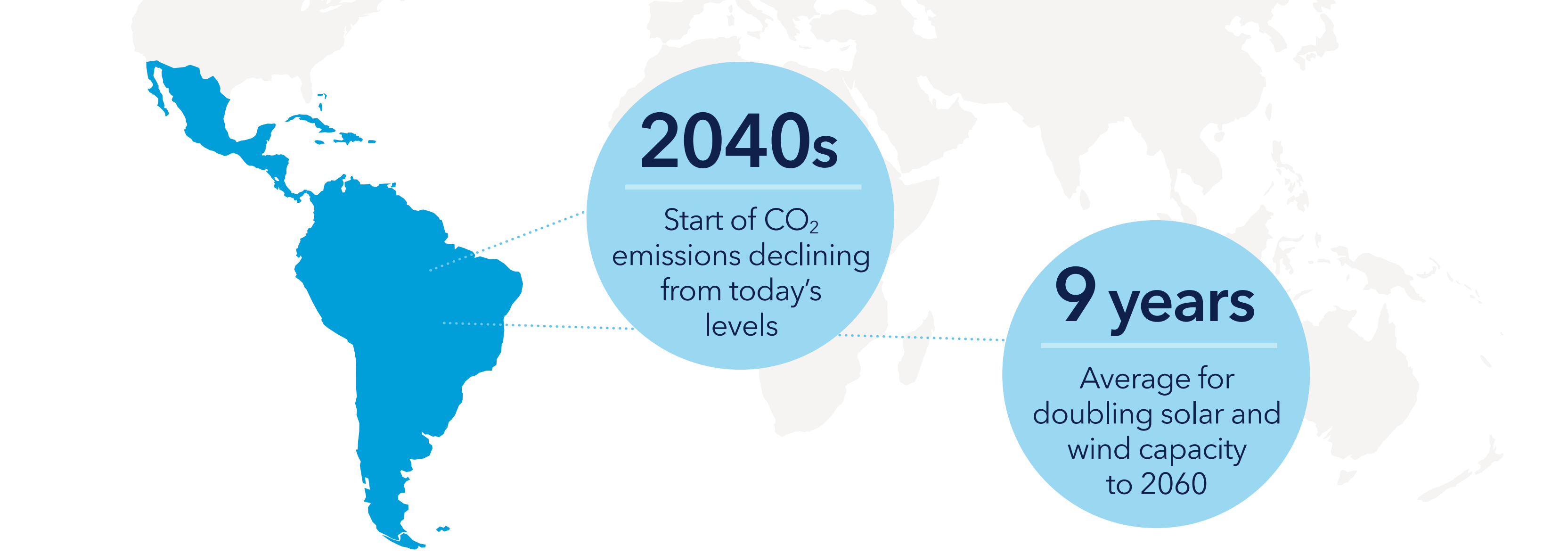


FIGURE 9.8 | OECD Pacific has the highest share of nuclear in grid-connected electricity of all regions from the late 2020s to 2060.
Fossil fuels includes coal-, gas-, and oil-fired; other renewables includes geothermal, bioenergy, hydropower; offshore wind includes fixed and floating.

LATIN AMERICA

Latin America's energy transition balances vast renewable resources with significant fossil fuel reliance. We forecast strong renewable growth, particularly in power, alongside persistent oil demand in transport and industry shaping its unique decarbonization pathway.



- **Power sector transformation:** We forecast Latin America's electricity generation will become 80% renewable by 2040 and 99% by 2060, with solar PV and wind power progressively replacing hydropower as the main source.
- **Surging electrification:** We forecast electricity's share in the region's final energy demand will more than double from 19% in 2024 to almost 45% by 2060, underpinning decarbonization efforts in road transport and buildings.
- **Modest hydrogen uptake:** While Latin America has strong potential for green hydrogen and its derivatives, we forecast these will meet only a modest share of energy demand: 1% by 2040 and 5% by 2060.
- **Emissions decline post-peak:** Having peaked around 2015, we forecast Latin America's energy related CO_2 will decline to half of 2024 levels by 2060, though oil's persistence freezes decarbonization until 2040.

READ THE FULL REGIONAL OUTLOOK HERE

Oil's lasting presence

Of all regions, Latin America currently has the highest share of oil in primary energy consumption (40%). The region will hold this position through to 2060, placing deeper decarbonization goals at risk despite significant progress with renewable energy (effectively halving the share of oil in primary energy). This persistence is rooted in both established oil production and continuing patterns of demand.

On the supply side, major oil-producing nations like Brazil, Mexico, and Venezuela possess vast reserves and the established infrastructure to exploit them.

The revenue from these oil exports is vital to their national economies, which ensures that production will remain substantial even if it declines from its peak levels.

On the demand side, the transportation sector is the main consumer. The region has extensive biofuel production and EV adoption is accelerating in the region's wealthiest countries. However, the high level of gasoline subsidies in some major economies also delays the decline of oil consumption. Industry also contributes to this sustained demand, particularly petrochemicals which require oil as a primary raw material or feedstock.

Oil consumption only starts declining in the 2040s, with transport as the main demand sector

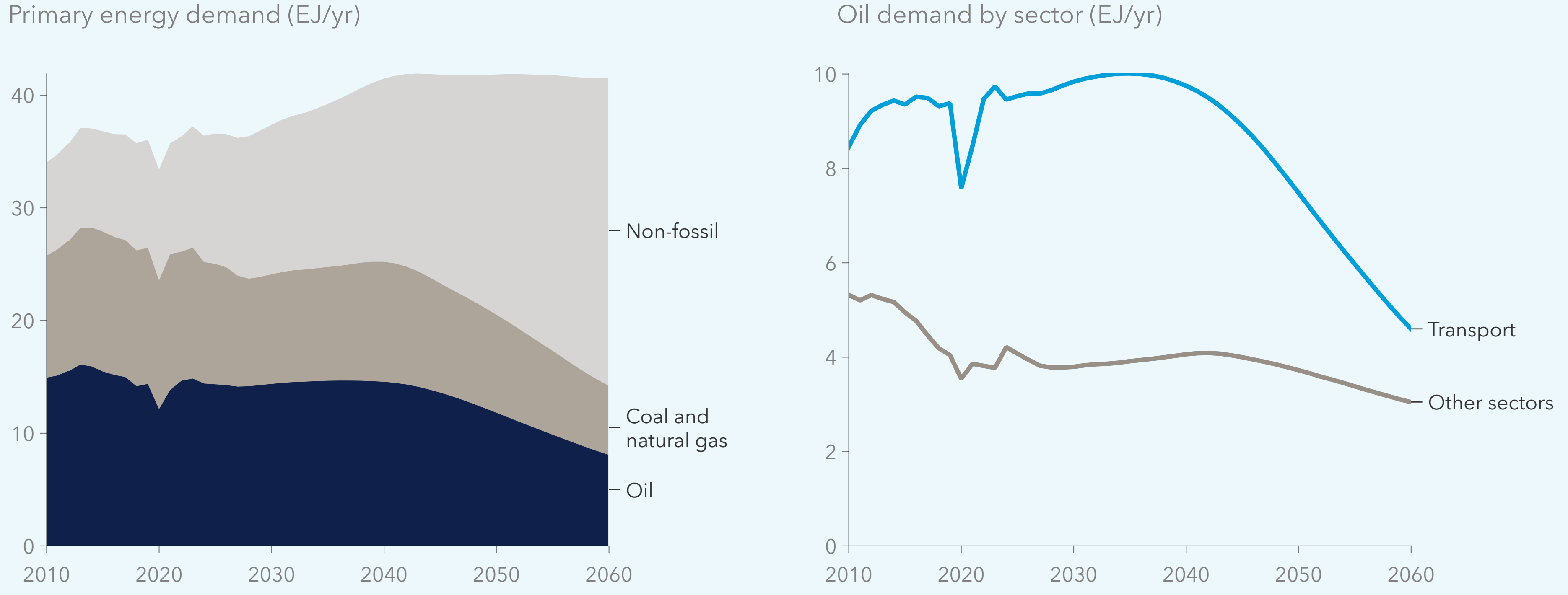
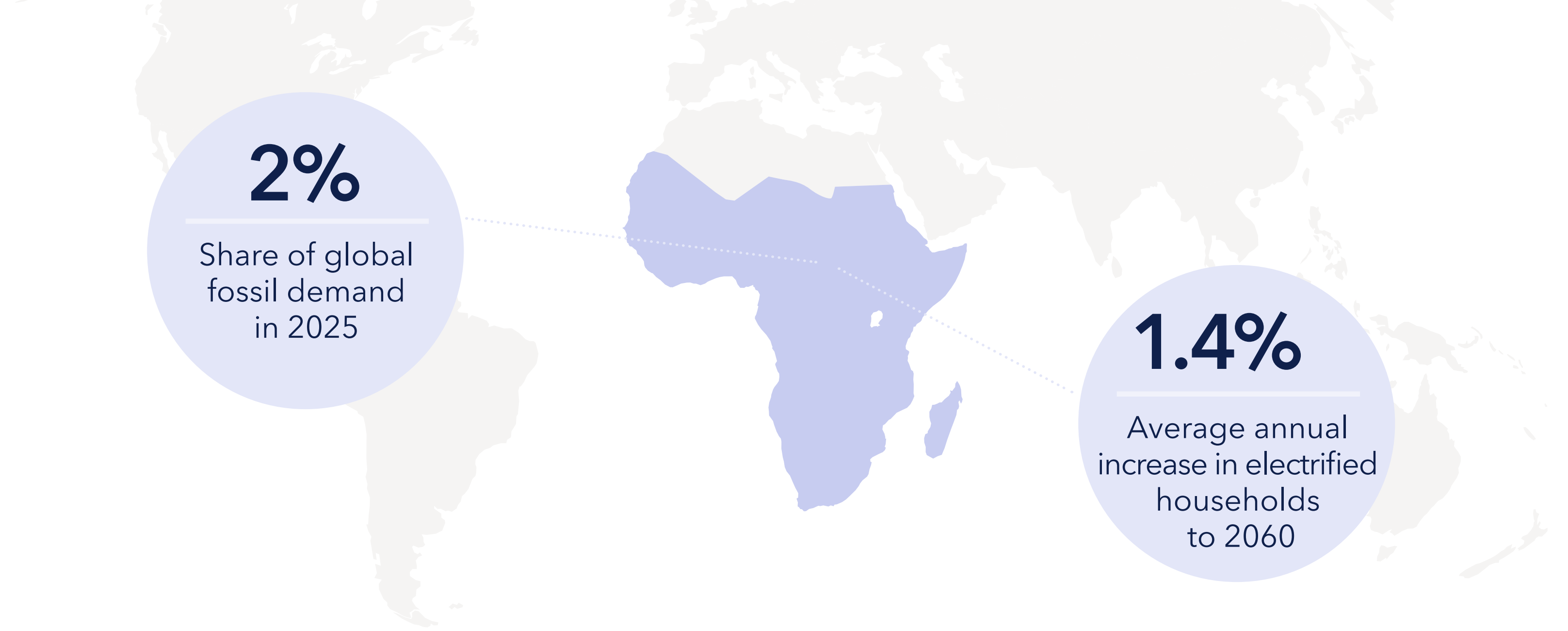


FIGURE 9.9 | Historical data source: IEA WEB (2025)

SUB-SAHARAN AFRICA

Sub-Saharan Africa's electricity supply will largely leapfrog fossil fuels, but electrification will not be fast enough to achieve universal access by 2060, hindering industrialization and development.



- Sub-Saharan Africa's electricity mix today comprises 61% fossil generation, 38% of which is coal. This will rapidly decarbonize to just 4% fossil by 2060.
- Electricity only supplies 9% of current energy demand. The two largest carriers are biomass at 55% and oil at 28%. Electrification of energy demand will proceed slowly, reaching 18% by 2060 at which time biomass and fossil sources will still supply 36% and 44%, respectively.
- Universal electricity access remains the region's main challenge. 85% of the 666 million people worldwide that lack access to electricity reside in this region (IRENA, 2025).
- Despite the population doubling by 2060, low economic growth results in a modest per capita energy demand trajectory that increases by only 12% and remains the lowest of our regions throughout the forecast period.

READ THE FULL REGIONAL OUTLOOK HERE

Enabling Africa's transition by expanding access

Electrification is a higher priority to the region's governments than their energy transition. However, low GDP per capita is the biggest challenge: with marginal or no disposable income, 45% of the population currently relies on traditional biomass for cooking and heating.

Increased electricity access is correlated to increased GDP per capita (Our World in Data, 2023). This is a mutually reinforcing relationship. Gaining access to electricity improves health and education outcomes and bolsters household finances and the purchasing of electric appliances (Banerjee, 2021). Rising electricity demand enables investment in generation and transmission technologies. This is sorely needed in a region that currently achieves less than a fifth of the global average per capita energy investment (IEA, 2025).

Small rooftop solar systems are bypassing the slow rollout of gridded electricity, spreading through sales processes reminiscent of the recent telecom boom. We expect that by 2060, only 8% of the population will not have electricity and 67% will have gained limited access through off-grid solar power. Only 2% of the population will still be reliant on diesel generators by then.

67% of households will gain electricity from off-grid solar

Share of households by mode of electricity access

Electricity demand by carrier in residential buildings (TWh/yr)

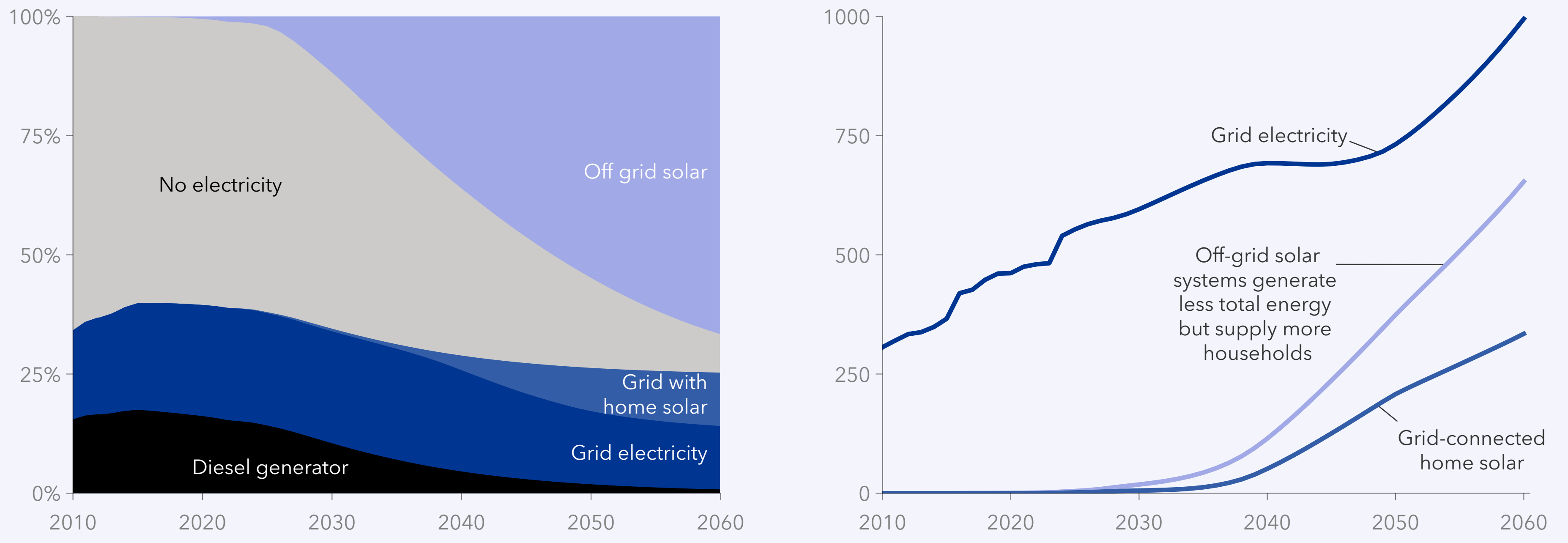


FIGURE 9.10 | Grid with home solar and off-grid solar includes systems with battery storage.
Historical data source: IEA WEB (2025)

10 THE ETO MODEL

10.1 SYSTEMS THINKING: HOW WE MODEL THE INTERCONNECTIONS IN THE ENERGY SYSTEM

Why systems thinking matters for the energy transition

The energy system is no longer a set of isolated sectors. Electrification, digitalization, and decentralization are creating ever-tighter interconnections across carriers, technologies, and users. Yet decisions are still often made in silos. 96% of power sector leaders call for urgent investment in grids, but 86% believe policymakers do not grasp the system-wide challenges (DNV, 2025). Systems thinking – the basis of our forecast – addresses this gap by focusing on the interactions, constraints, and feedback loops that shape long-term outcomes.

Structure over snapshots: Capturing system behaviour

Transitions do not unfold in straight lines. They are shaped by feedback loops, delays, and competition between technologies. Learning effects, infrastructure constraints, and investor responses all influence outcomes over time. These dynamics cannot be captured in static models or spreadsheets. A structured system model is needed to reflect how parts of the energy system interact, reinforce, or offset one another. Without this, even well-informed forecasts risk overlooking what ultimately drives change.

Why system dynamics?

System dynamics is a method for simulating how complex systems behave over time. It sits within the broader tradition of systems thinking and is designed to capture how feedback loops, time delays, and limited decision-making shape outcomes. In energy transitions, these features are critical. We use system dynamics to model how investors, producers, consumers, and governments respond to changing signals under uncertainty. It is well suited for long-term dynamics where outcomes depend on how the system evolves, not on static assumptions.

Forecasting system behaviour

The ETO is a simulation-based forecast that reflects how the energy system behaves under a most-likely scenario. It is not a best-case pathway or a cost-optimized solution. Instead, it considers how different parts of the system interact over time, shaped by known constraints and real-world decision making.

What makes this approach distinctive is its focus on system response. We do not assume that choices are perfect or coordinated. We account for how policies, technologies, and behaviours influence one another, sometimes in unexpected ways. Falling battery costs can accelerate EV adoption, which both raises electricity demand and, through vehicle-to-grid services, can feed power back to the grid. As the system transitions, these cross-sector links grow in number and importance – what once happened in isolation now has knock-on effects across the whole system. A model that captures these connections becomes not just useful, but essential. Figure 10.1 highlights a selection of such feedback loops. They are not side effects but core drivers of how the system evolves.

Simplified model structure and selected key feedback loops in the ETO Model

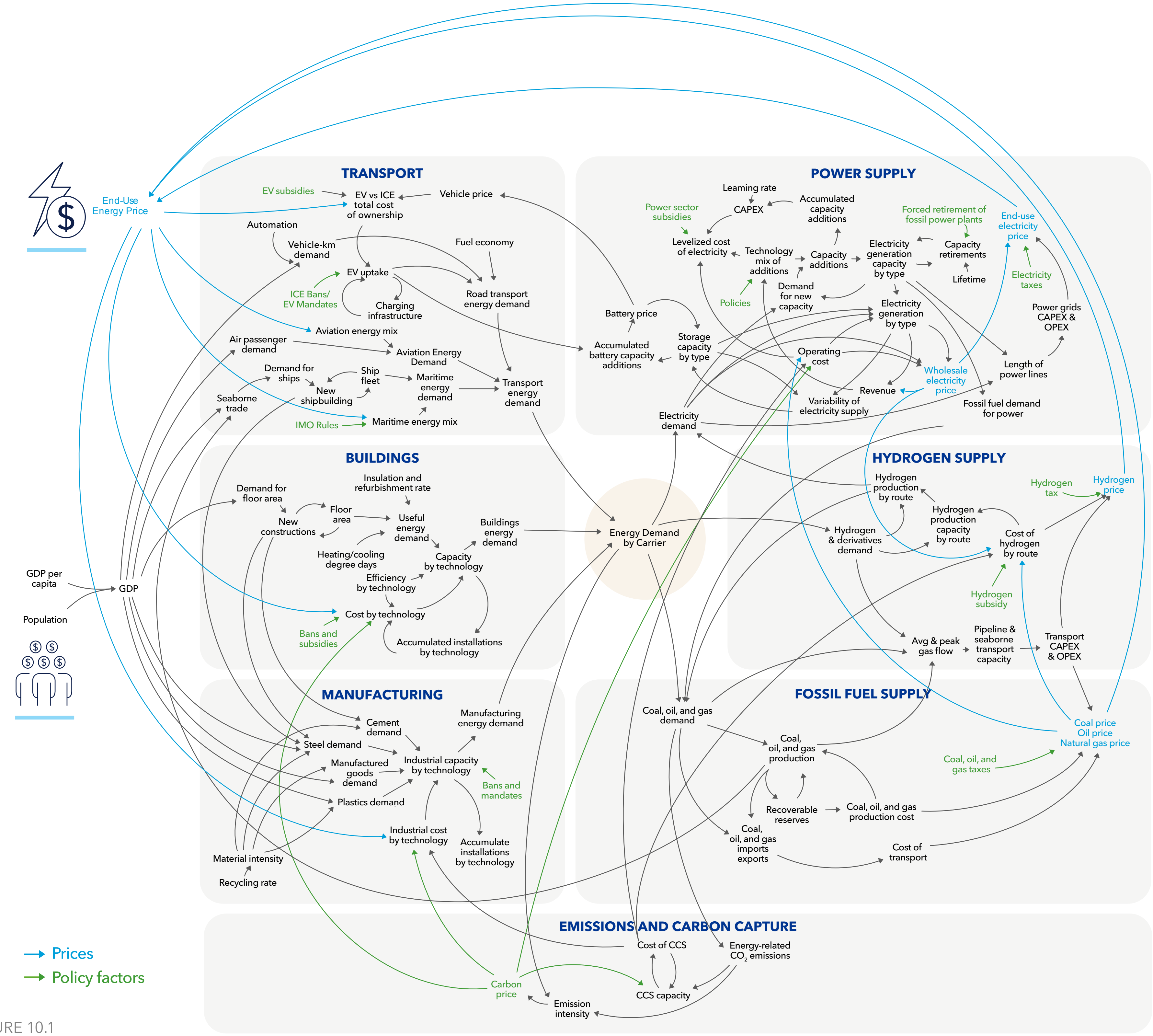


FIGURE 10.1

10.2 HOW THE ETO MODEL OPERATES

A long-term, behaviourally-grounded forecast

The ETO Model simulates the global energy system from 1980 to 2100. This long horizon allows us to represent gradual structural change in technology, demand, supply, and investment. Electricity dispatch is simulated hourly to capture grid flexibility and variability; other sectors run on weekly time steps. The model does not optimize for least cost or best case. Instead, it projects the most likely path forward, based on real-world constraints and feedback loops.

Decisions based on real information

We do not assume perfect foresight or centralized planning. Instead, we model how households, companies, and governments act based on what they know, what they value, and the options they face. Investors weigh expected returns. Households care about upfront costs and convenience. Governments pursue a mix of economic, social, and strategic goals. These actors act incrementally, not globally. Their choices are bounded, interdependent, and shape the behaviour of the system itself.

Policy, timing, and constraints

In our model, policy is implemented as it exists in reality – through taxes, subsidies, mandates, and bans. The model includes delays where they matter: in planning, permitting, construction, and learning. It also captures limitations on how quickly supply chains can ramp up, how quickly consumers can adopt new technologies, and how long assets stay in use. These frictions, often overlooked in simple models, are essential for understanding transition speed and direction.

Granularity where it matters

The model covers 10 world regions, 12 energy carriers, and over 20 end-use sectors including transport, buildings, and manufacturing (Figure 10.2). This structure allows us to capture fuel switching, technology competition, and regional differences in cost, policy, and behaviour. It also reflects the energy used by whom, for what, and with which technology – critical to understanding system interactions.

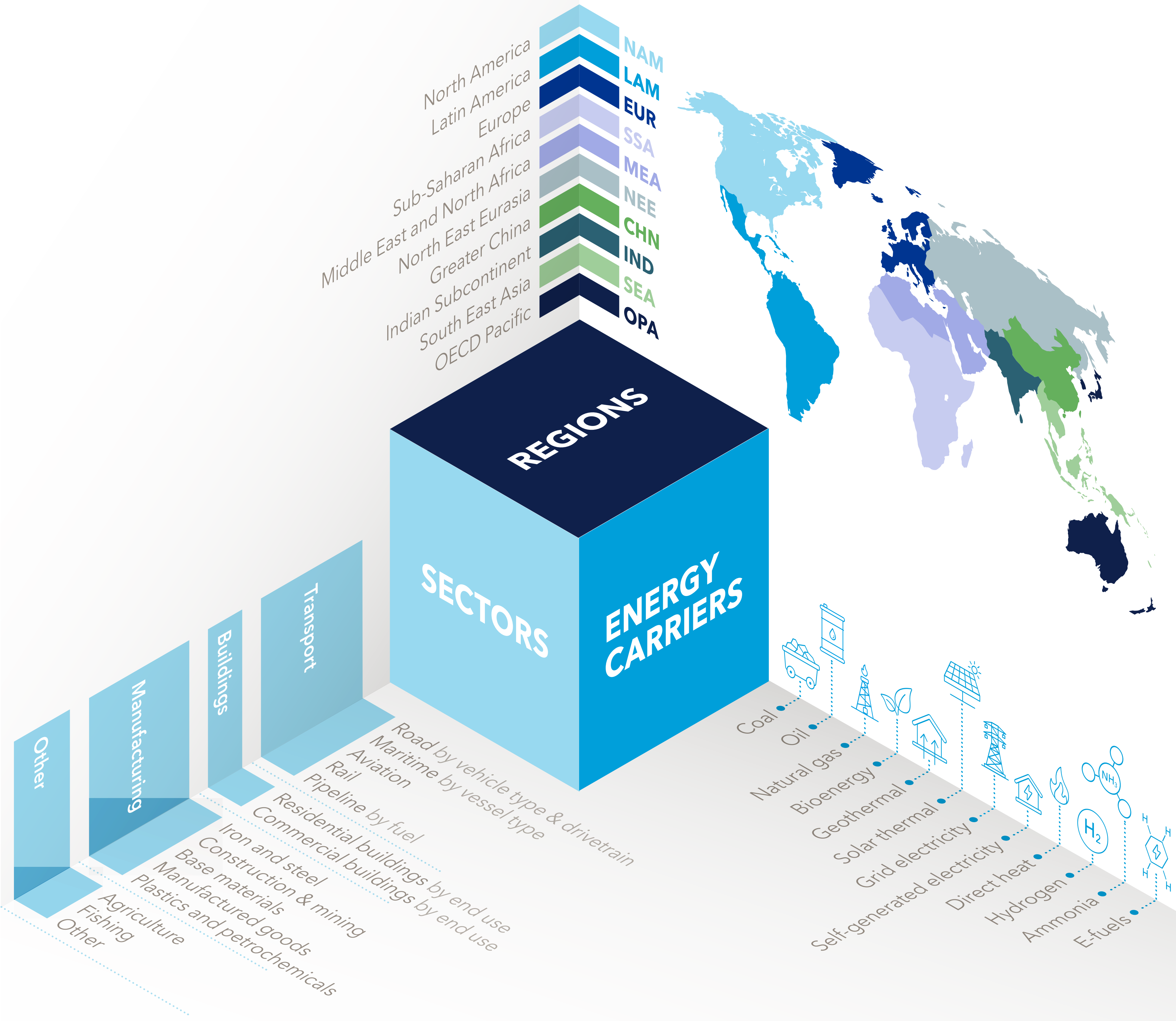
Data driven and continuously updated

Model parameters are grounded in data from trusted sources such as the IEA, UN, GlobalData, and Comtrade. These are supplemented by DNV's expert insights and internal research. We regularly update the model to reflect new policy, cost trajectories, and observed market trends. Sensitivity tests are used to test assumptions and improve robustness. The result is a model that reflects how the energy system works – not how we might wish it to.

For further information on our use of systems thinking, you may wish to consult:

DNV, 2025. *From Silos to Systems: The Importance of Whole Energy Systems Thinking.* Energy Industry Insights 2025 Special Report.

ETO model granularity



10.3 WHAT'S NEW IN THE ETO MODEL THIS YEAR

Each year, we refine the ETO Model to reflect the latest data, technology trends and policy developments.

Macroeconomic outlook
The GDP trajectory has been revised downwards. In the short term, this reflects the IMF's latest outlook. Over the long term, we adopt a blend of SSP2 and SSP3, judged to be the most likely scenario. This has implications for energy demand, investment levels, and emissions trends.

Policy and market shifts
The model now incorporates policies driven by energy security concerns. These include homeshoring of manufacturing, protective trade tariffs, and the energy impact of increased defence spending. We updated regional variations in cost of capital and assumed different technology progress rates for Western and Eastern country groups.

Data centres
We introduce a long-term causal formulation for data centre energy use. It includes feedback loops between computing performance and demand, as well as constraints related to chip production and grid capacity. Server costs and chip sizes are now endogenous. The model also distinguishes between general-purpose and AI-focused data centres, reflecting their growing divergence.

Behind-the-meter generation
A new module now captures the full cost of ownership and uptake dynamics of behind-the-meter solar and battery systems. It covers both residential and commercial buildings and allows cost, policy, and convenience factors to drive behind-the-meter deployment over time.

Carbon capture and carbon dioxide removal
CCS is now modelled with greater detail, including a wider range of applications, updated cost assumptions, and project pipelines. Carbon dioxide removal technologies (BECCS and DAC) are integrated through a market-based approach. Process emissions and CCS transport and storage are treated explicitly.

Carbon pricing
Carbon prices after 2035 are now linked to both the emissions level and the rate of change in emissions. This creates a more dynamic price signal that reflects progress (or lack of it) in decarbonization.

Grid bottlenecks
A new formulation introduces constraints on electricity generation and demand growth due to transmission and distribution grid limitations. These bottlenecks are driven by transformer availability and infrastructure rollout capacity, creating feedback loops that can slow electrification.

District heating
A new formulation estimates district heating potential based on geospatial analysis. It uses population density and heating demand distribution to identify where district heating is viable and likely to grow.

Bioenergy supply
Bioenergy modelling now includes increased granularity in feedstock types and regional supply potential.

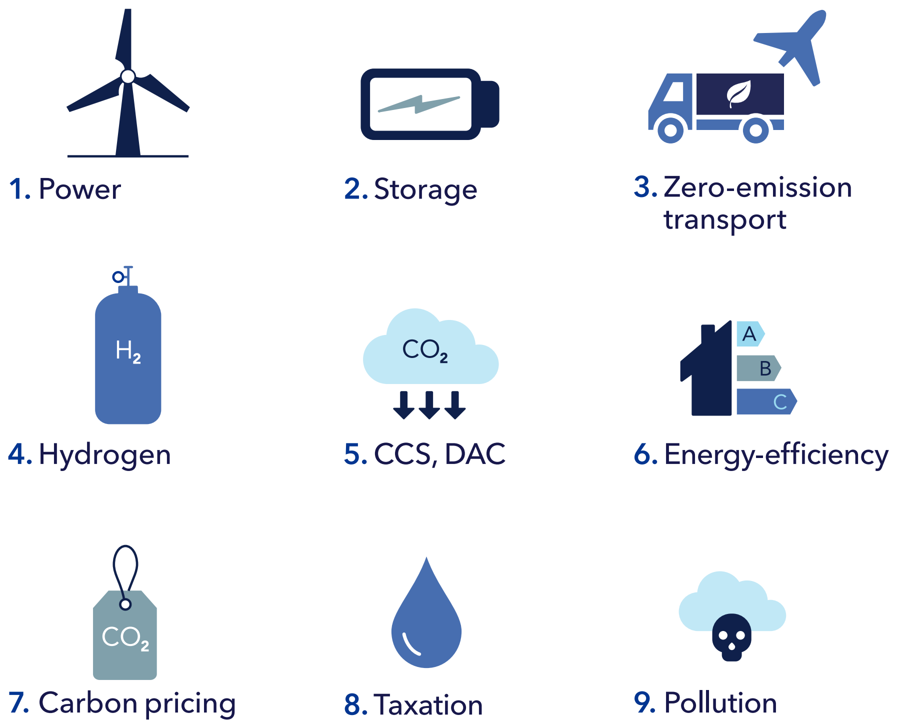
Oil and gas production
We revised production cost parameters for oil and gas. The model now applies a simplified classification of field types across regions.

10.4 POLICY FACTORS IN THE ETO MODEL

Each year, we refine the ETO Model to reflect the latest data, technology trends, and policy developments.

Our forecast factors in policy measures spanning the entire policy toolbox outlined in Chapter 6. These affect energy transition dynamics in three main ways: supporting technology development and deployment, applying technology requirements or standards, and impacting prices. Nine policy factor areas and implementation in the ETO Model are summarized to the right.

Policy factors included in our Outlook



1. Power

Includes renewable power support from auctions (CfDs, PPAs), investment or production cost support (FiTs, FiPs, tax credits), and behind-the-meter solar PV support for buildings.

We account for fuel and technology import dependency and reflect energy security policy via regionally differentiated preferential treatment of domestic sources (solar, wind, coal, gas, nuclear) with incentives/disincentives as a percentage of LCOE.

We incorporated phase-out plans of nuclear, coal, and natural gas.

2. Storage

Includes average regional support for battery storage technologies expressed as a percentage of battery unit costs.

Support levels rise with the share of variable renewables in regional electricity generation, which promote investment in flexibility, while reflecting regional differences in policy ambition and capacity for implementing support.

Includes historical support for behind-the-meter storage for residential and commercial buildings.

3. Zero-emission transport

Road includes average regional CAPEX support for battery-electric (BEV) and fuel-cell electric vehicles (FCEV), accounting for subsidies, tax exemptions and import duty reductions. This support declines over time and is capped by cost disadvantage. We factor in grid constraints limiting charging infrastructure uptake. Refuelling infrastructure (H_2) support reflects public funding.

Shipping and aviation includes fuel-mix shifts driven by carbon price, fuel-blending mandates, investment support, and GHG fuel intensity requirements (IMO, 2025).

4. Hydrogen

Includes production, infrastructure, buildings and manufacturing support, either CAPEX (% capital cost) based on government funding or OPEX subsidies (auctions / tax credits) – whichever is higher and varying by region. We assume full subsidies until 2030 and gradually halve them to 2050 unless specific end-data is available.

Grid-based electrolysis (EUR) reflects emission intensity thresholds, adding a premium to sourcing renewable electricity. The model aligns with additionality and hourly temporal matching requirements. CCS in low-carbon hydrogen production is mainly driven by carbon prices.

5. CCS & DAC

Includes historical and planned CCS capacity through 2032, adjusted for project maturity and risk. These projects are the 'policy-driven' capacity expectations receiving investment and operational support from governments.

We integrate regional policy support beyond this pipeline based on current targets and funding. Support declines as CCS costs approach carbon prices and is modelled as capital subsidies or per-tonne incentives like the US 45-Q.

DAC support reflects government funding to CAPEX.

6. Energy efficiency

Building standards for insulation and energy use guide input assumptions, though policy effects are not explicitly quantified. In Europe, higher retrofit rates reflect subsidies and tax credits for insulation and weatherization.

Vehicles standards are regionally adjusted to real-world fuel use via NEDC correction factors, guiding fuel-efficiency trajectories to 2050 and accounting for EV adoption.

Shipping includes regulations: *Ship Energy Efficiency Management Plan* (SEEMP), CII, *Energy Efficiency Existing Ship Index* (EEXI), and GHG fuel Intensity requirements (IMO, 2025).

7. Carbon pricing

Is reflected as costs for fossil fuels in manufacturing, power, hydrogen, ammonia, and methanol production, assuming participation in the same regional schemes. Carbon pricing also applies to methane abatement in the energy system. Exemptions and free allowances are included (e.g. EU CBAM policy). Buildings have a separate carbon price trajectory to reflect the ETS-2 scheme in Europe.

The regional trajectory to 2035 is based on policy announcements and trends in existing and planned schemes. From 2035 onwards, we determine carbon prices endogenously, based on regional emission intensity trends in the manufacturing and power sectors.

8. Taxation

Road transport includes fuel/carbon taxes incorporated in fuel prices, rising with regional carbon prices. Some regions maintain fossil-fuel subsidies.

Buildings and industry include energy taxes that encourage electrification and hydrogen, the latter is also VAT-exempt in industry (all regions).

For grid-connected electrolysers, a 10% addition to wholesale electricity reflects subsidized taxes and grid tariffs.

Transport includes taxes on electricity calculated from the share of charging types and their prices compared with the residential price, and applied in regions, excluding those with fossil-fuel subsidies.

9. Pollution

Air pollution prevention: includes an air pollution cost proxy, added as an operating cost per kWh in power and manufacturing with regionally differentiated implementation (0% to full cost over time) reflecting increasing enforcement of pollution controls.

Plastic pollution intervention: includes recycling mandates, taxes, trade restrictions, and EPR, represented by recycling rates and demand reductions via substitution. Europe leads implementation, with other regions following 5 to 15 years later.

10.5 ASSUMPTIONS (GDP, POPULATION)

Some parameters in the ETO Model are not directly derived from the analysis but are imposed as exogenous factors that drive energy demand. Two such factors are the population and economic projections, both globally and for each of the 10 world regions we model.

Population
We base our forecast on population data from the UN Department of Economic and Social Affairs and the Wittgenstein Centre for Demography and Global Human Capital. We use the UN data as the historical reference and the Wittgenstein Centre data, which were last published in 2023 and runs to 2100, as a forecast (Wittgenstein, 2023).

The Wittgenstein Centre has developed scenarios that correspond to the five 'Shared Socioeconomic Pathways (SSP)' used by the Inter-governmental Panel on Climate Change. In this Outlook, we follow the central scenario (SSP2) for population, often called the 'Middle of the Road', and use it as a source of inspiration for other exogenous forecast inputs. Using this approach, we arrive at our 2060 population forecast of 9.9 billion. This is an increase of 21% from today's population of 8.2 billion (UN, 2025). By 2060, the global population will still be growing, but the rate is reduced to 0.3% per year; Sub-Saharan Africa will be the only region with notable growth and six of our 10 regions will already be declining.

Our 2060 projection is 1% lower than the latest UN median estimate of 10 billion. The UN median population projection and the Wittgenstein Centre numbers have been converging in recent updates, with some minor regional variations. The main uncertainty in population lies in the long term (2100 and beyond) forecast; most mainstream forecasts, including the UN's, now indicate global population will peak around 2080 and then decline.

GDP and productivity
GDP per capita is a measure of the standard of living in a country and is a major driver of energy consumption. It is also a good proxy for labour productivity, as it reflects the amount of economic output per person, and thus is also used as one of the drivers of demand in several places in the ETO Model (vehicle ownership, housing size, etc.).

We base our GDP per capita forecast to 2030 on the GDP per capita growth rates implied by the latest update of the *World Economic Outlook* by IMF (2025). Our projections to 2060 are based on the GDP per capita growth rates implied by OECD (2024) and Applied Systems Analysis (IIASA, 2024).

However, due to the current geopolitical landscape and uncertainties in future economic development, we deviate this year from following a pure central scenario (SSP2) for GDP per capita growth. Instead, we combine two pathways, SSP2 and SSP3, and use the average, based on both OECD and IIASA data, indicating a slower GDP per capita growth trajectory. The implication is that we no longer assume that future economic developments will continue along historical trends. However, we also do not assume that we will transition purely to SSP3 ('Regional rivalry pathway') and have therefore chosen a development between these two trajectories (see Table 10.1 for comparison). While we assume a slower overall trajectory, we have included a modest 'AI dividend', based on the recent IMF short-term forecast (Reuters, 2025). Over the long term, our lower-growth pathway already builds in a modest AI-related productivity boost, following OECD (2025). Beyond 2035, the size of this boost is highly uncertain, so we hold it constant – a deliberately conservative choice.

For our GDP projection, while we assume a slower overall trajectory, we have included a modest 'AI dividend' based on the recent IMF forecast.

Comparison of Shared Socioeconomic Pathways (SSPs)

SSP2 – 'Middle of the Road'	SSP3 – 'Regional Rivalry: A Rocky Road'
Envisions a balanced economic trajectory with room for global cooperation and gradual improvements.	Reflects a world where economic nationalism, weak institutions, and lack of coordination cause economic stagnation and deepening global inequality.
Narrative summary: – Continuation of historical trends without major disruptions. – No major shifts in policies, governance, or societal behaviour. – Development and income growth proceed unevenly, with some convergence but persistent inequalities.	**Narrative summary:** – A fragmented world characterized by nationalism, regional conflicts, and limited international cooperation. – Nations prioritize security and self-sufficiency over global trade and sustainability. – Development is slow and uneven, especially in poorer countries.

TABLE 10.1

We expect world GDP to grow from USD 177trn/yr in 2024 to USD 347trn/yr in 2060. This is a near doubling of the economy over the next 36 years. However, the different regions contribute differently, with OECD countries growing much slower compared to developing economies.

The world experienced a 3.2% compound annual GDP growth from 2000 to 2020 (Table 10.2). In the 2040s, this will gradually slow to 1.6%/yr as a result of the slowdown in population growth and the economies of more and more countries becoming service orientated. Nonetheless, most economies around the world will continue to grow with likely exceptions only in mature economies that are experiencing marked population decline. The fastest growth in GDP per capita between 2024 and 2030 will be in Asia. The Indian Subcontinent will have the highest growth rate at an average of 5.4%/yr, followed by Greater China at 4.3%/yr, and South East Asia at 3.7%/yr.

Compound annual GDP growth rate by region (in %)

		2000-2020	2020-2030	2030-2040	2040-2050	2050-2060	2020-2060
NAM	North America	1.9%	2.2%	1.1%	1.0%	1.0%	1.3%
LAM	Latin America	2.0%	2.4%	2.3%	2.0%	1.6%	2.1%
EUR	Europe	1.2%	1.6%	1.1%	0.8%	0.7%	1.1%
SSA	Sub-Saharan Africa	4.2%	4.0%	4.3%	3.7%	3.3%	3.8%
MEA	Middle East and North Africa	3.6%	3.7%	2.7%	2.2%	1.8%	2.6%
NEE	North East Eurasia	3.4%	2.3%	1.5%	1.1%	1.0%	1.5%
CHN	Greater China	8.1%	4.3%	1.8%	1.3%	0.7%	2.0%
IND	Indian Subcontinent	6.1%	6.3%	3.4%	2.6%	2.2%	3.6%
SEA	South East Asia	4.8%	4.4%	2.8%	2.0%	1.6%	2.7%
OPA	OECD Pacific	1.4%	1.3%	0.9%	0.5%	0.2%	0.7%
	World	**3.2%**	**3.2%**	**2.0%**	**1.6%**	**1.3%**	**2.1%**

TABLE 10.2

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